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McCall et al.

(10) **Patent No.: US 6,671,648 B2**
(45) **Date of Patent: *Dec. 30, 2003**

(54) **MICRO INERTIAL MEASUREMENT UNIT**

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(73) Assignee: **American GNC Corporation**, Simi Valley, CA (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 84 days.

This patent is subject to a terminal disclaimer.

(21) Appl. No.: **10/017,310**

(22) Filed: **Oct. 22, 2001**

(65) **Prior Publication Data**

US 2002/0065626 A1 May 30, 2002

Related U.S. Application Data

(62) Division of application No. 09/477,151, filed on Jan. 4, 2000.

(51) **Int. Cl.**[7] **G01P 5/00**; G01P 15/00
(52) **U.S. Cl.** **702/141**; 702/145
(58) **Field of Search** 702/127, 141, 702/142, 145, 151, 216; 701/217, 220, 221

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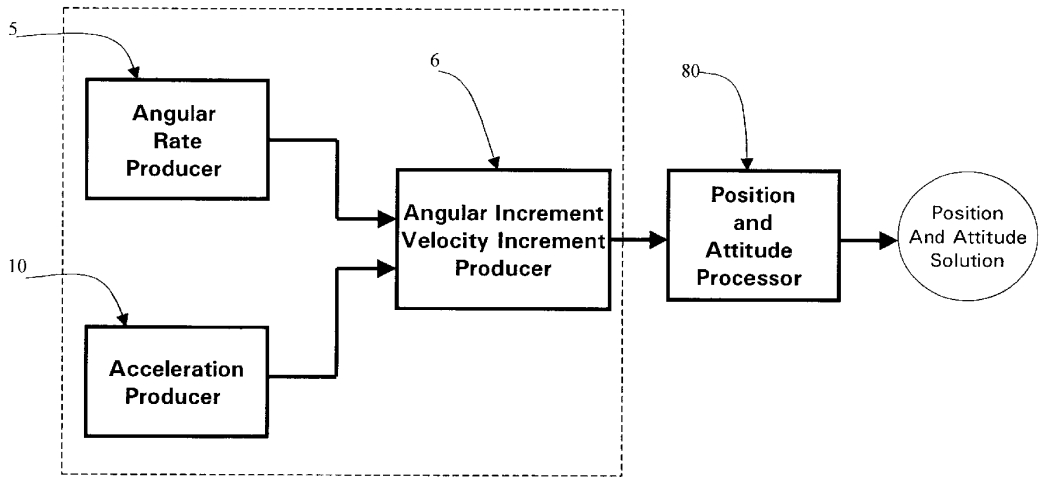
* cited by examiner

Primary Examiner—Bryan Bui
(74) *Attorney, Agent, or Firm*—Raymond Y. Chan; David and Raymond Patent Group

(57) **ABSTRACT**

A micro inertial measurement unit, which is adapted to apply to output signals proportional to rotation and translational motion of a carrier, respectively from angular rate sensors and acceleration sensors, is employed with MEMS rate and acceleration sensors. Compared with a conventional IMU, the processing method utilizes a feedforward open-loop signal processing scheme to obtain highly accurate motion measurements by means of signal digitizing, temperature control and compensation, sensor error and misalignment calibrations, attitude updating, and damping control loops, and dramatically shrinks the size of mechanical and electronic hardware and power consumption, meanwhile, obtains highly accurate motion measurements.

4 Claims, 26 Drawing Sheets



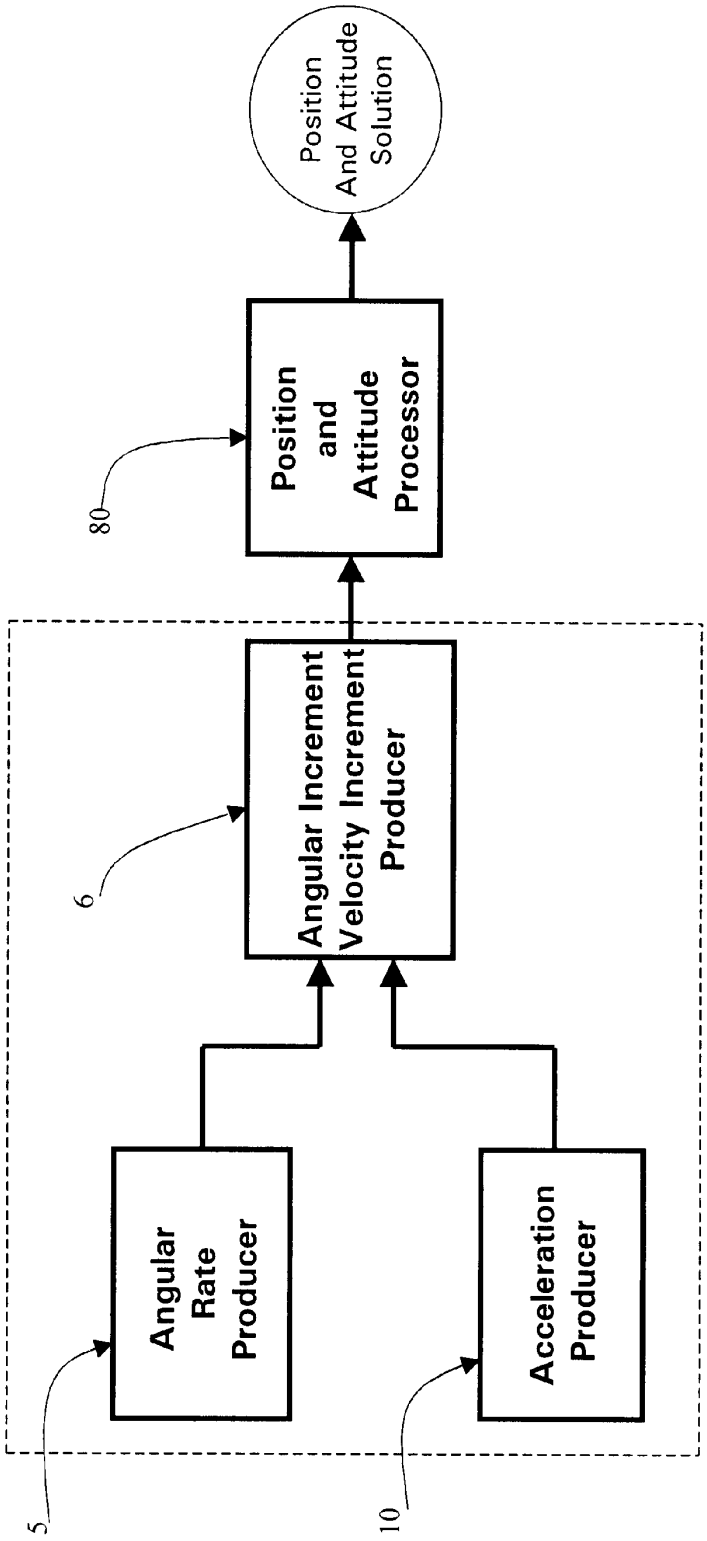

Position And Attitude Solution
Position and Attitude Processor
80
Angular Increment Velocity Increment Producer
6
Angular Rate Producer
Acceleration Producer
5
10

Figure 1

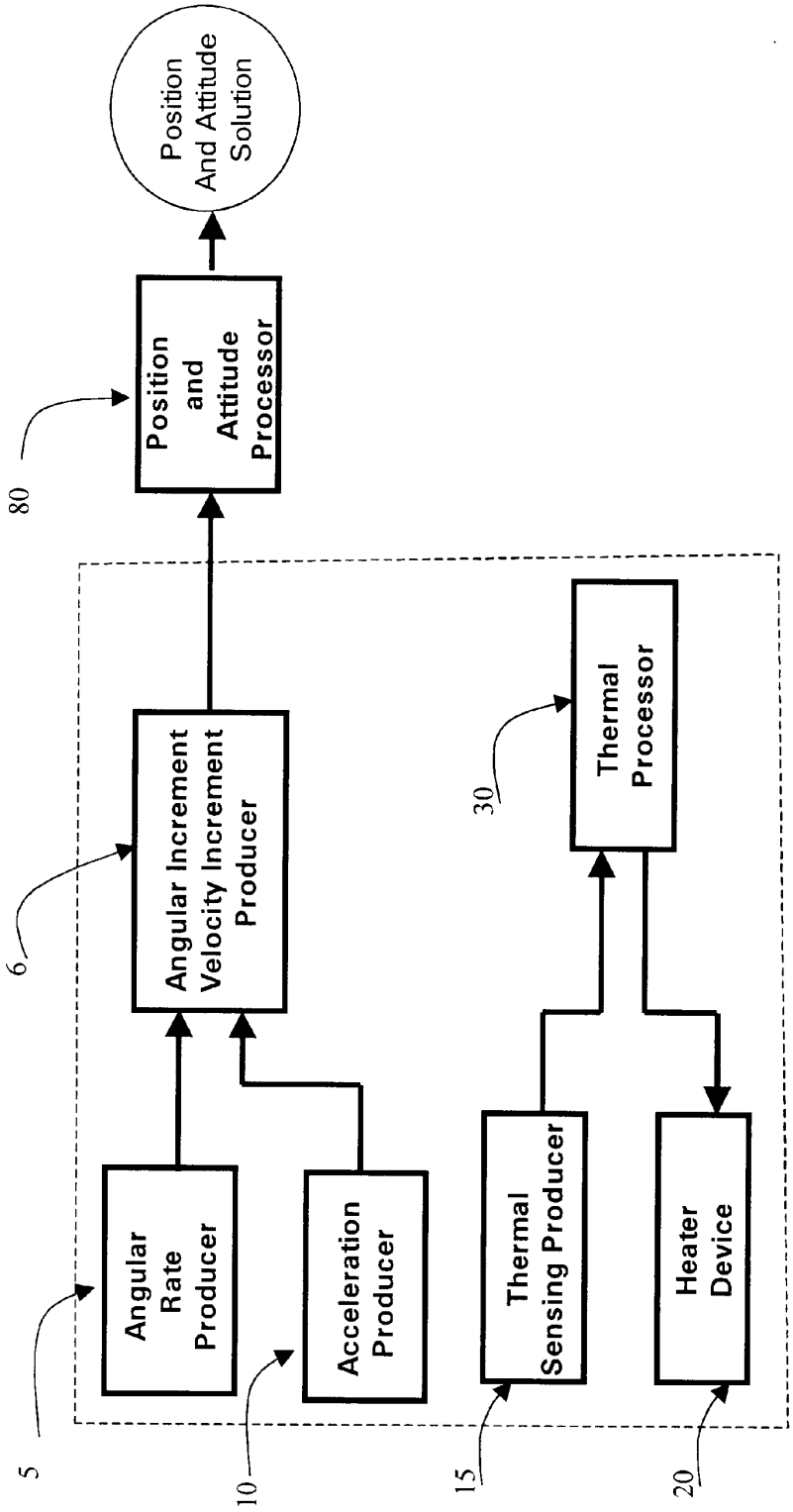

Position And Attitude Solution
Position and Attitude Processor
80
Angular Increment Velocity Increment Producer
6
Thermal Processor
30
Angular Rate Producer
Acceleration Producer
Thermal Sensing Producer
Heater Device
5
10
15
20

Figure 2

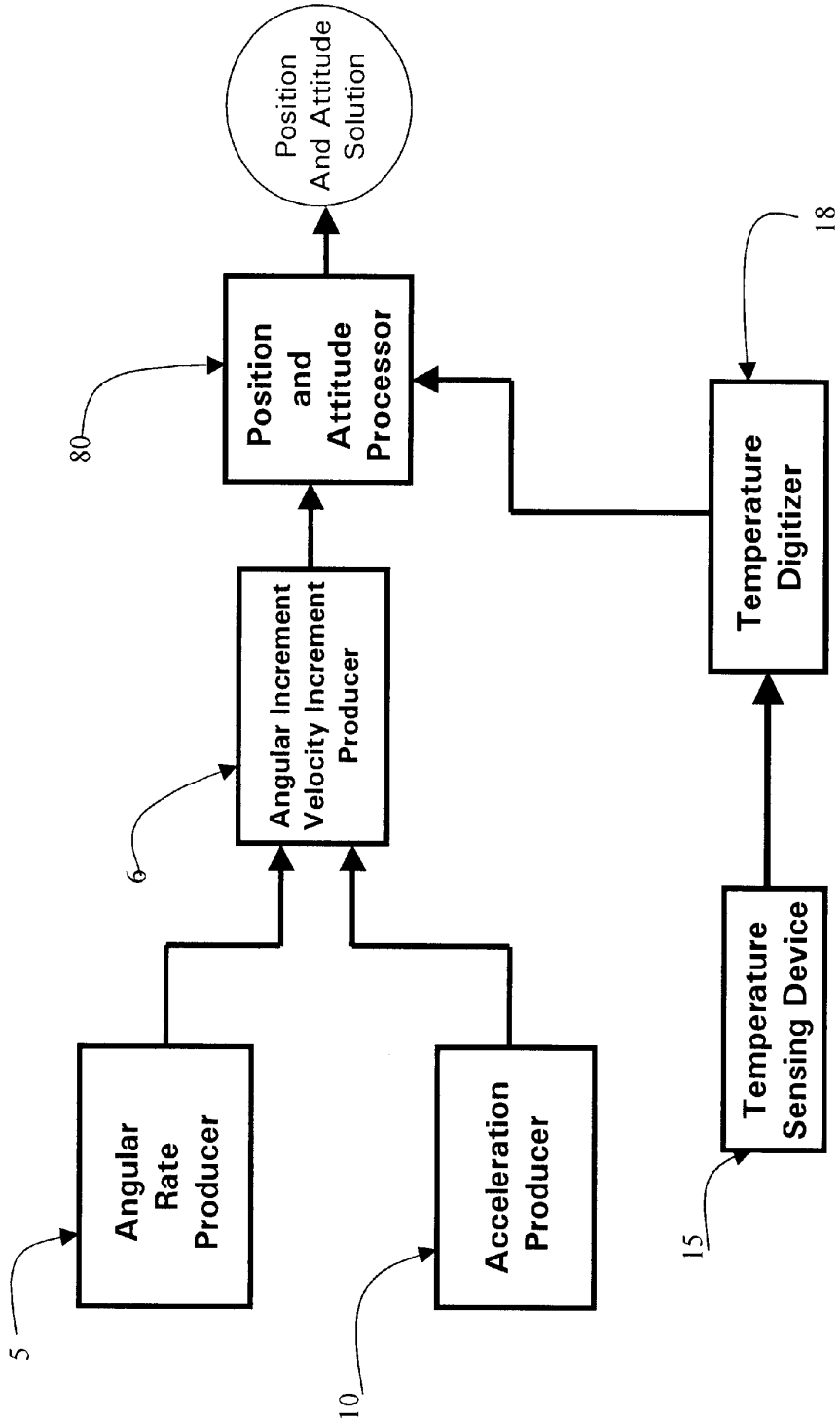

Position And Attitude Solution
Position and Attitude Processor
80
Angular Increment Velocity Increment Producer
6
Angular Rate Producer
5
Acceleration Producer
10
Temperature Digitizer
18
Temperature Sensing Device
15

Figure 3

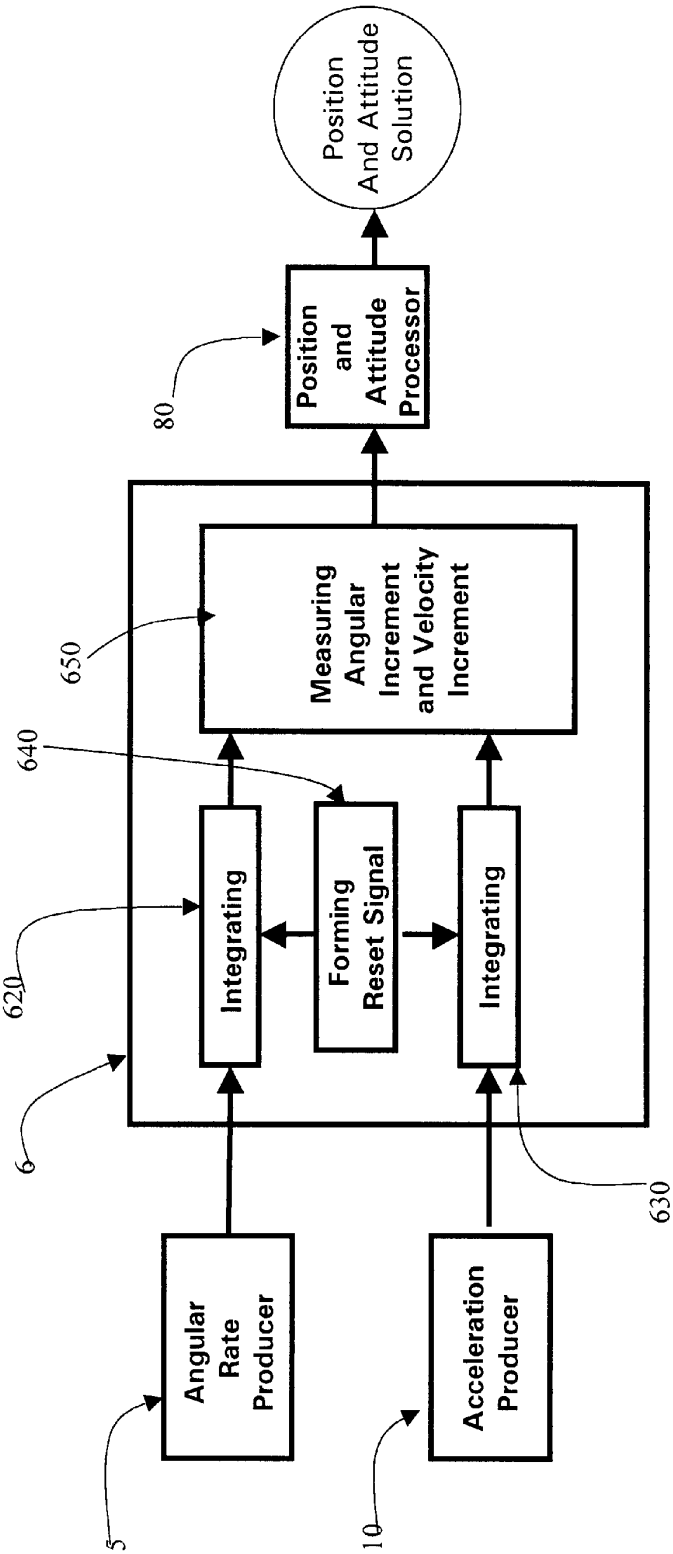

Position And Attitude Solution
80
Position and Attitude Processor
650
Measuring Angular Increment and Velocity Increment
640
620
Integrating
Forming Reset Signal
Integrating
6
630
Angular Rate Producer
Acceleration Producer
5
10

Figure 4

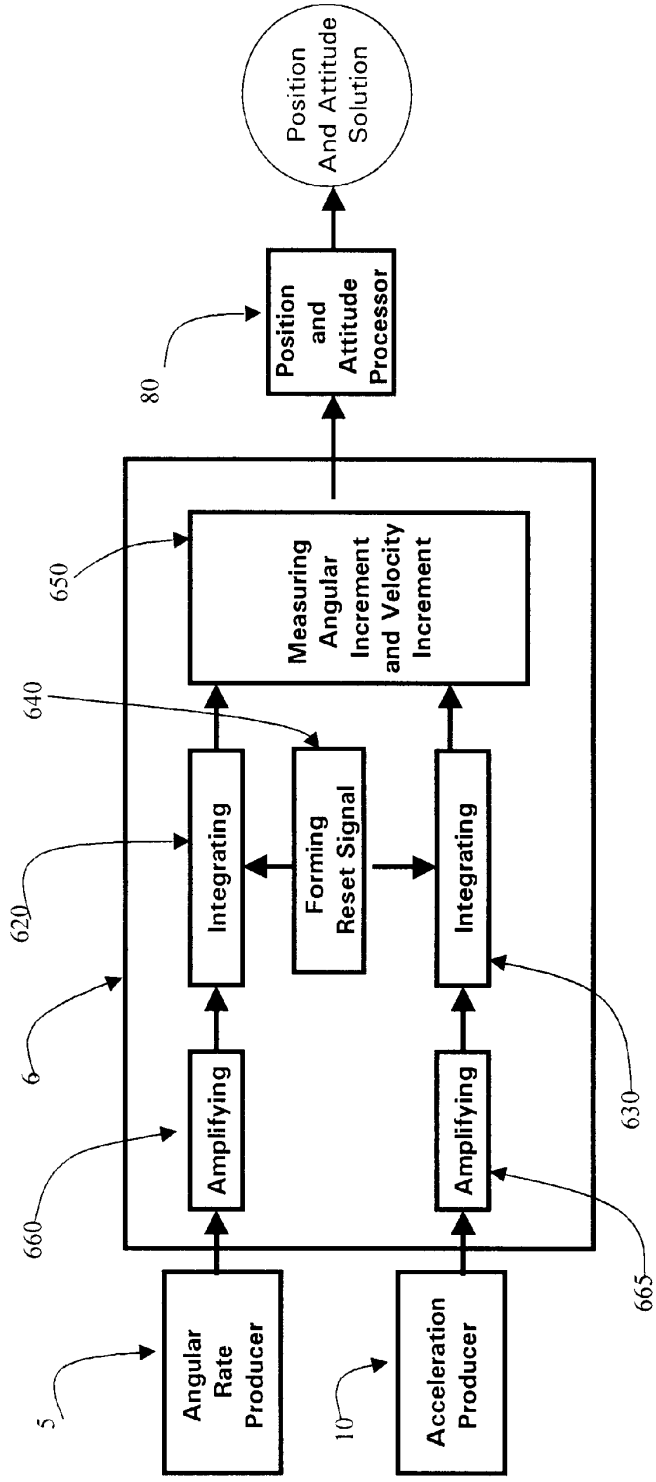

Position And Attitude Solution
80
Position and Attitude Processor
650
Measuring Angular Increment and Velocity Increment
640
620
Integrating
Forming Reset Signal
Integrating
6
660
Amplifying
Amplifying
630
665
5
Angular Rate Producer
10
Acceleration Producer

Figure 5

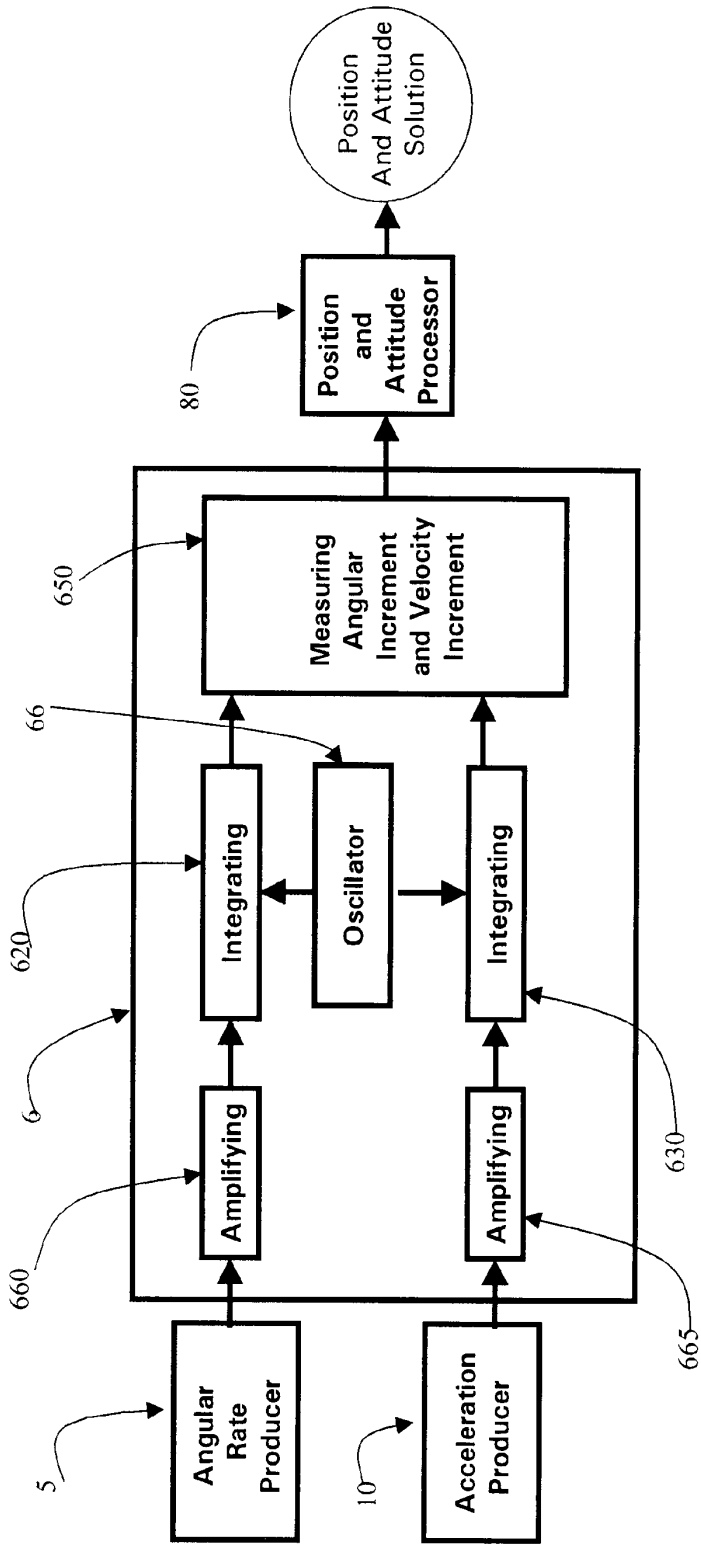

Position And Attitude Solution
80
Position and Attitude Processor
650
Measuring Angular Increment and Velocity Increment
66
620
Integrating
Oscillator
Integrating
6
630
660
Amplifying
Amplifying
665
5
Angular Rate Producer
10
Acceleration Producer

Figure 6

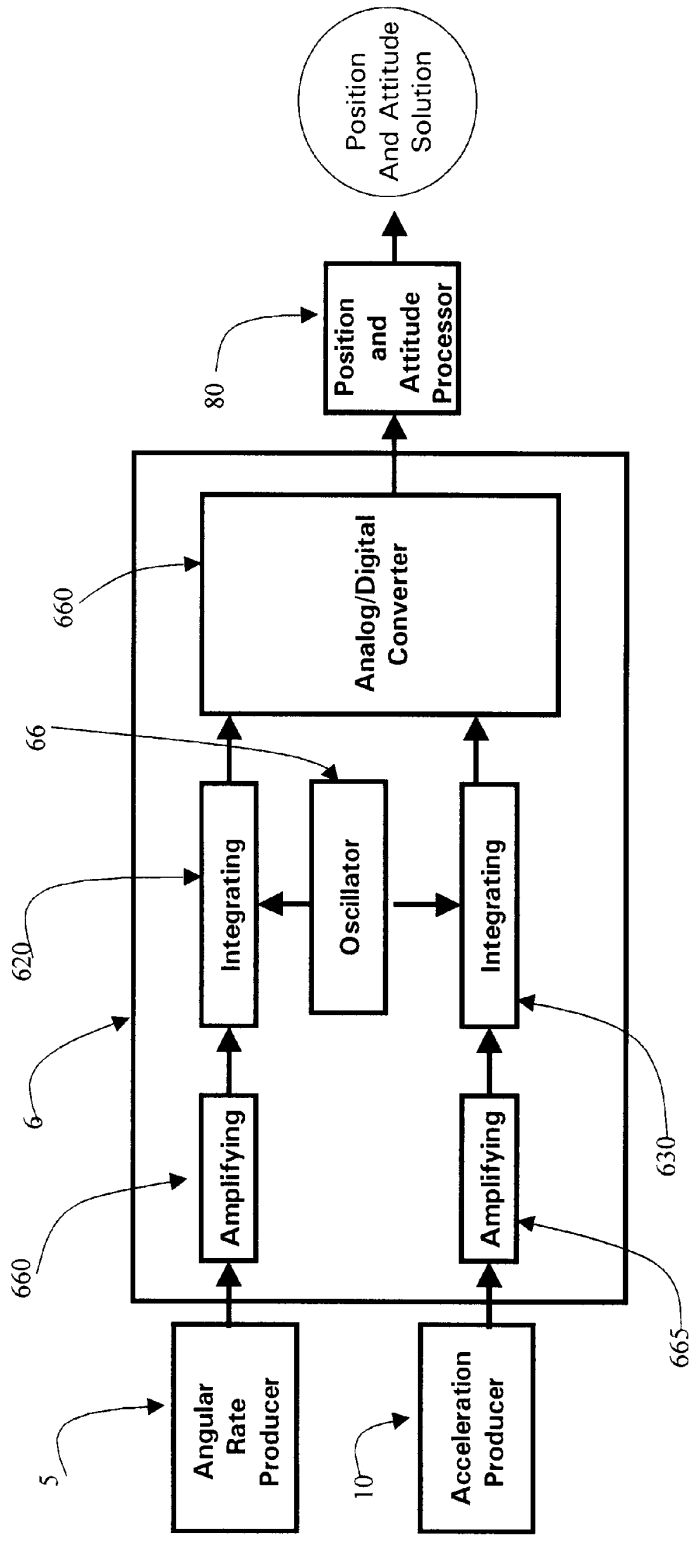

Position And Attitude Solution
80
Position and Attitude Processor
660
Analog/Digital Converter
66
620
Integrating
Oscillator
Integrating
6
630
660
Amplifying
Amplifying
665
5
Angular Rate Producer
10
Acceleration Producer

Figure 7

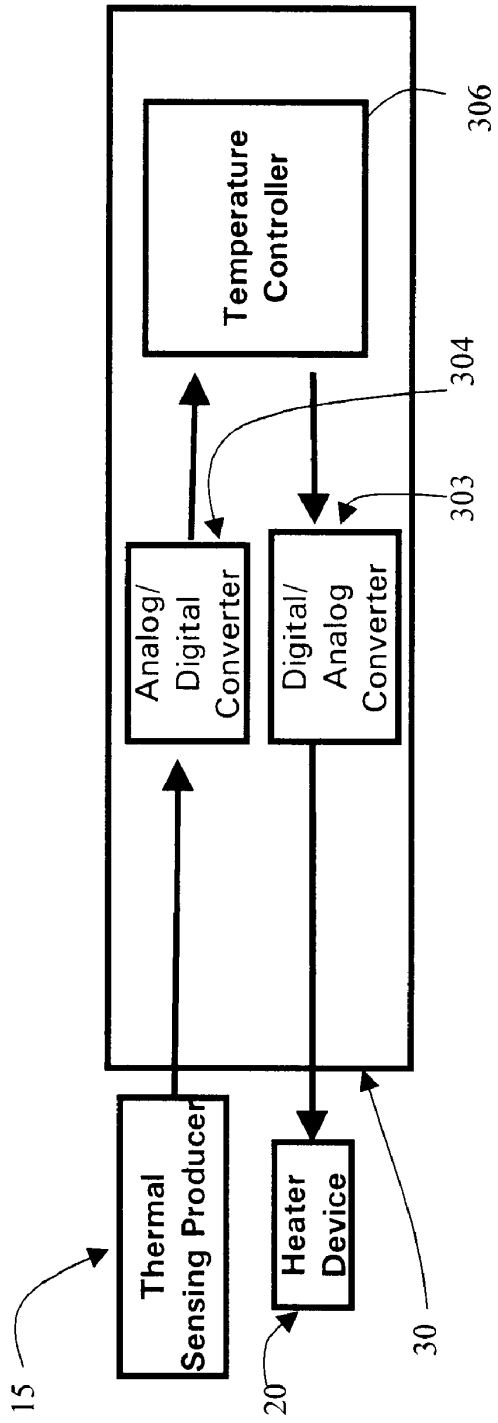

Temperature Controller
306
304
303
Analog/ Digital Converter
Digital/ Analog Converter
Thermal Sensing Producer
Heater Device
15
20
30

Figure 8

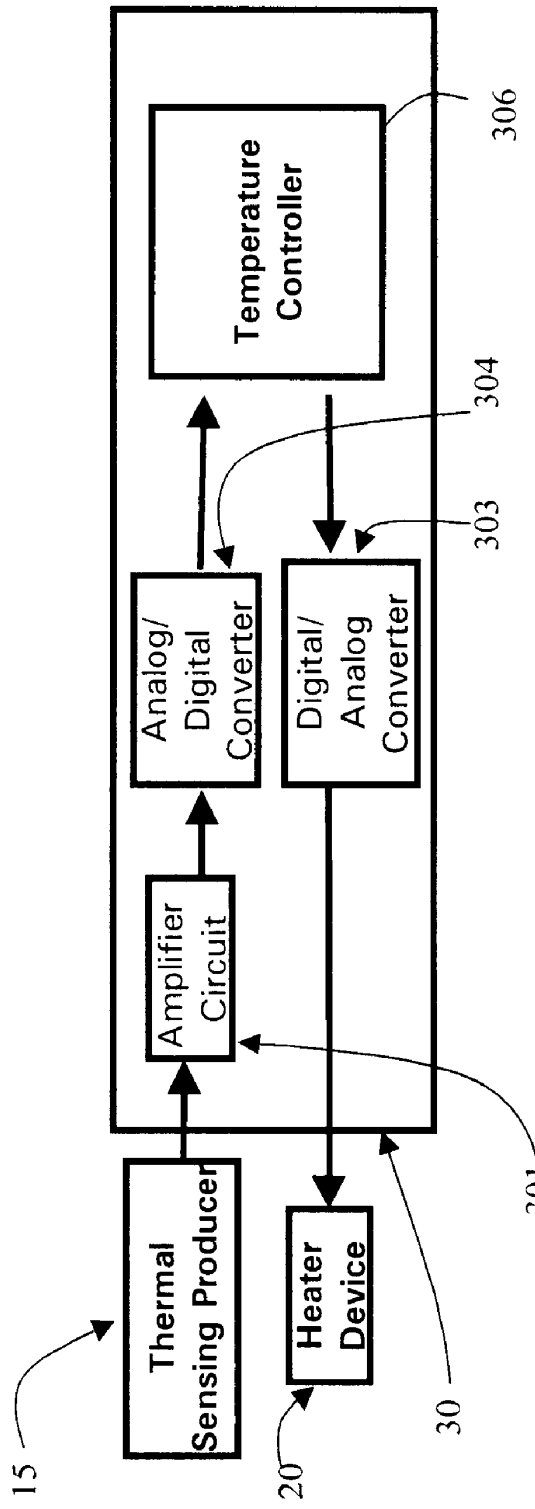

Temperature Controller
306
304
303
Analog/ Digital Converter
Digital/ Analog Converter
Amplifier Circuit
301
Thermal Sensing Producer
Heater Device
15
20
30

Figure 9

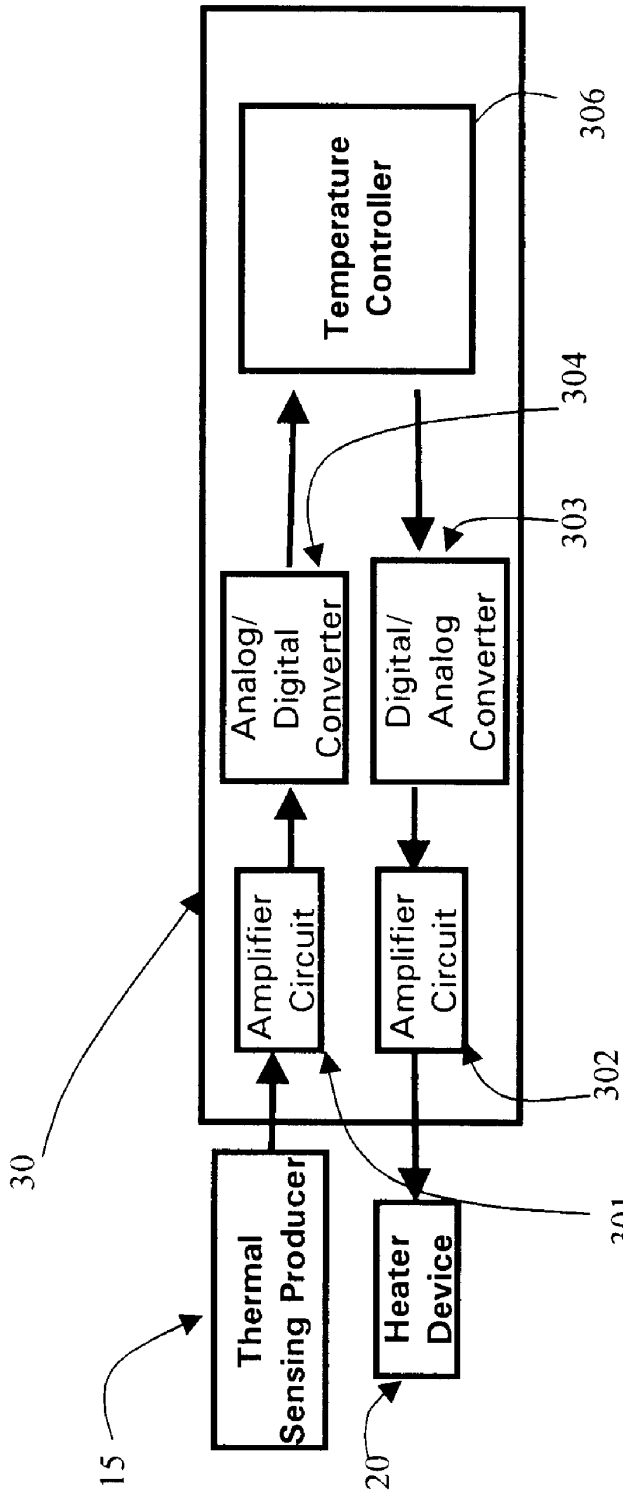

Temperature Controller
306
304
303
Analog/ Digital Converter
Digital/ Analog Converter
Amplifier Circuit
Amplifier Circuit
302
30
301
Thermal Sensing Producer
Heater Device
15
20

Figure 10

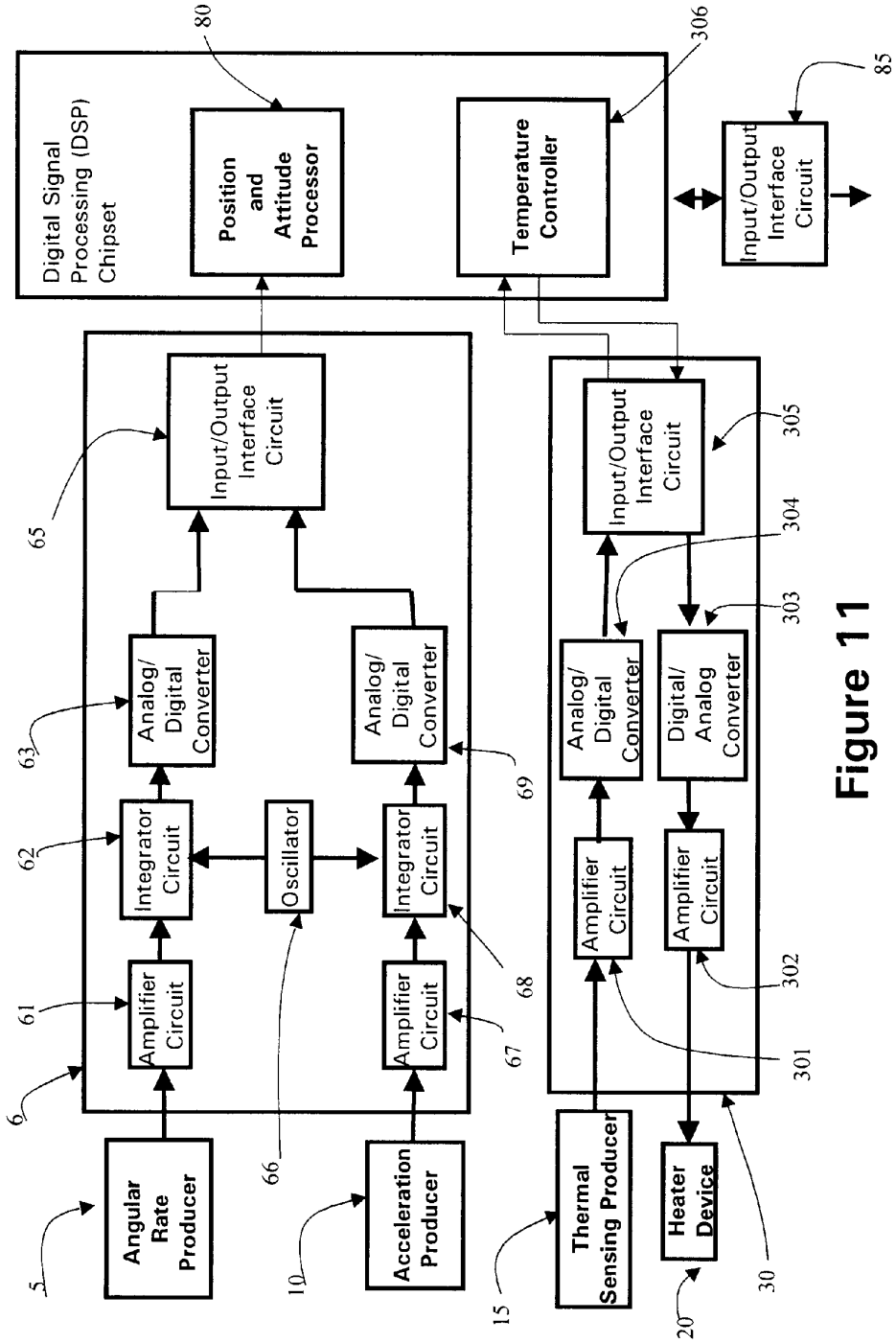

Digital Signal Processing (DSP) Chipset
80
Position and Attitude Processor
306
Temperature Controller
85
Input/Output Interface Circuit
65
Input/Output Interface Circuit
305
304
303
Analog/ Digital Converter
63
Analog/ Digital Converter
69
Analog/ Digital Converter
Digital/ Analog Converter
62
Integrator Circuit
Oscillator
Integrator Circuit
61
Amplifier Circuit
Amplifier Circuit
68
67
Amplifier Circuit
Amplifier Circuit
302
6
301
66
5
Angular Rate Producer
10
Acceleration Producer
15
Thermal Sensing Producer
20
Heater Device
30

Figure 11

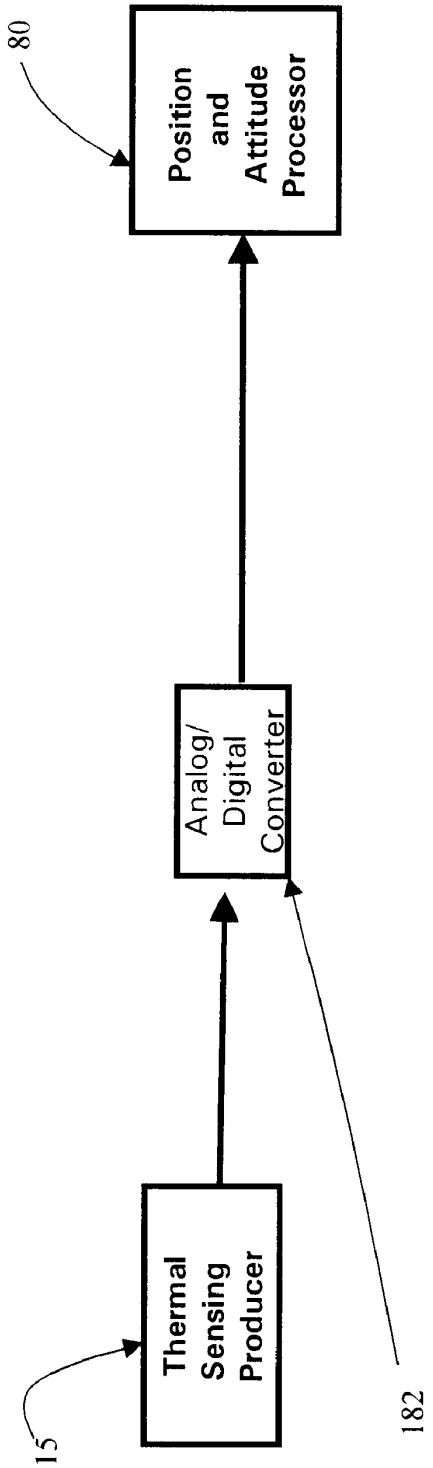

80
Position and Attitude Processor
Analog/ Digital Converter
Thermal Sensing Producer
15
182

Figure 12

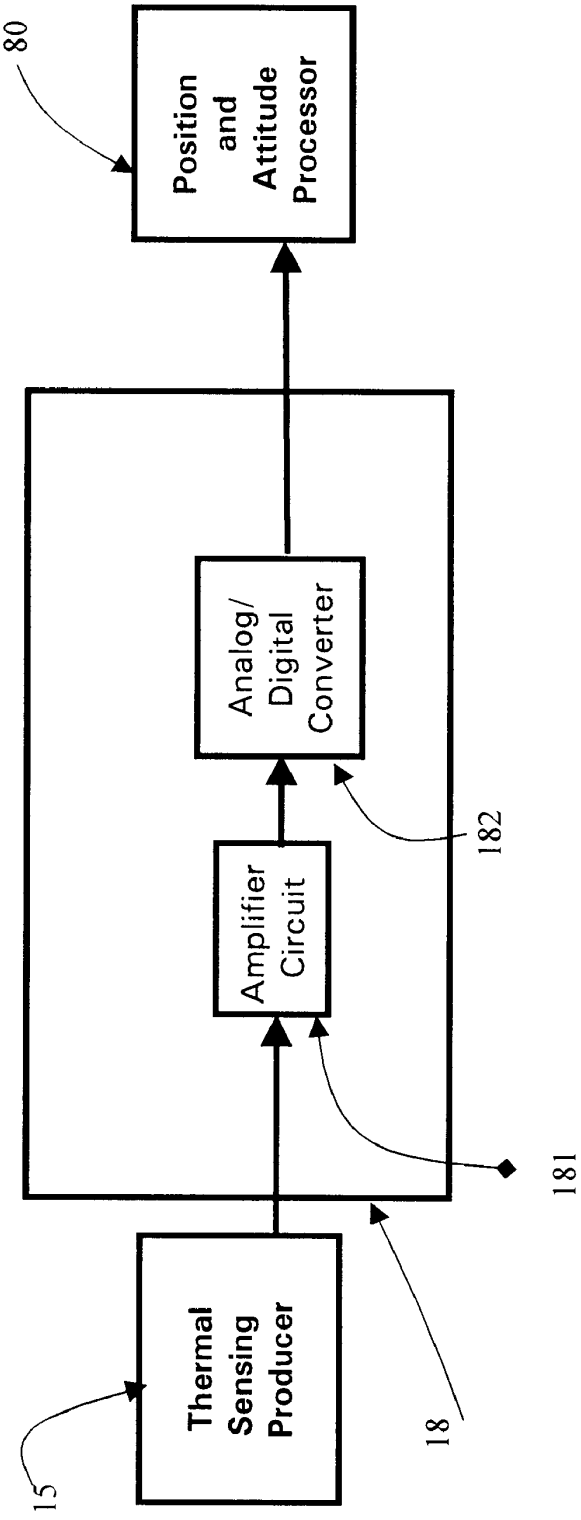

80
Position and Attitude Processor
Analog/ Digital Converter
182
Amplifier Circuit
181
Thermal Sensing Producer
15
18

Figure 13

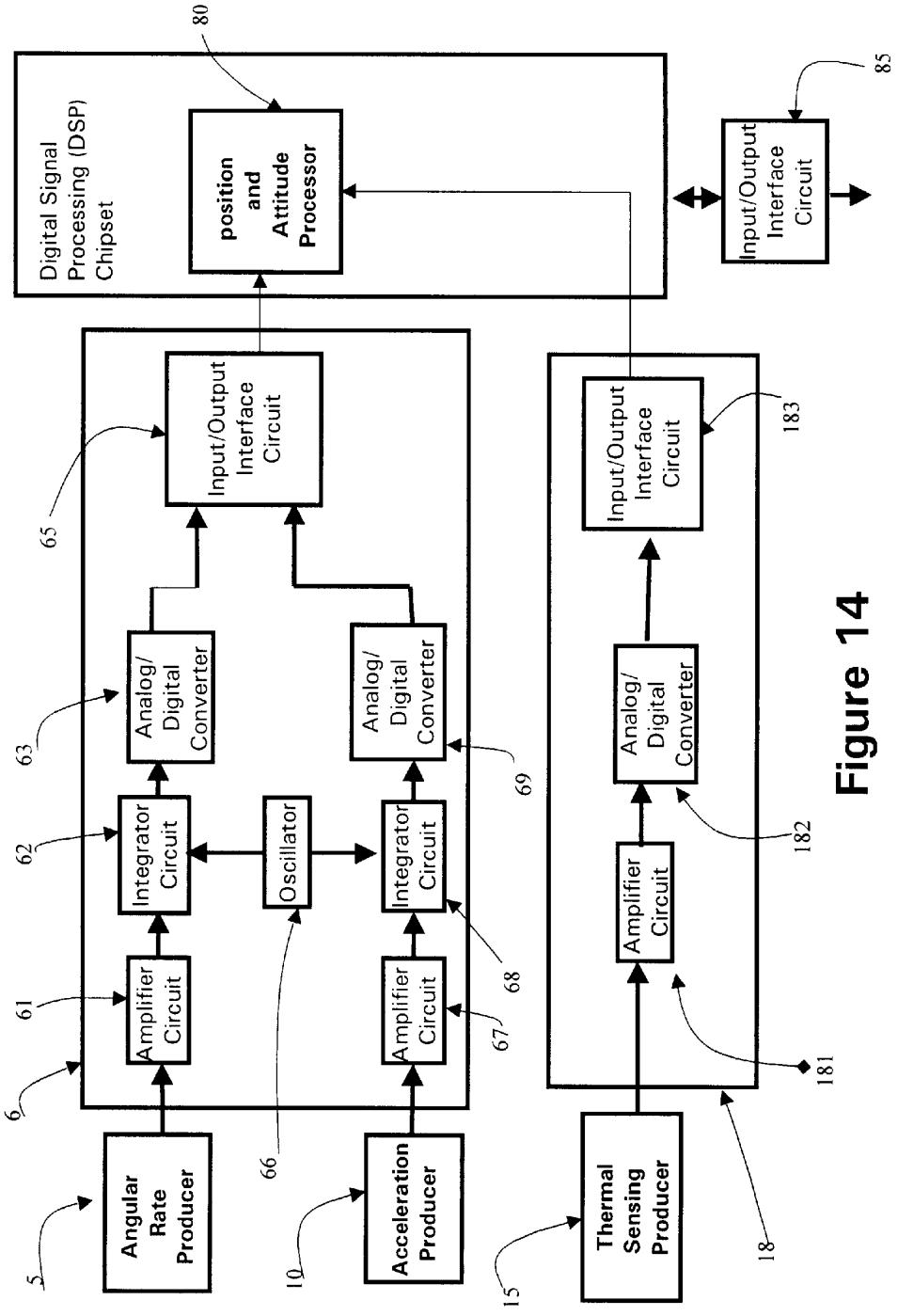

Digital Signal Processing (DSP) Chipset
position and Attitude Processor
80
Input/Output Interface Circuit
85
Input/Output Interface Circuit
65
Analog/ Digital Converter
63
Integrator Circuit
62
Amplifier Circuit
61
6
Oscillator
66
Analog/ Digital Converter
69
Integrator Circuit
68
Amplifier Circuit
67
Angular Rate Producer
5
Acceleration Producer
10
Input/Output Interface Circuit
183
Analog/ Digital Converter
182
Amplifier Circuit
181
Thermal Sensing Producer
15
18

Figure 14

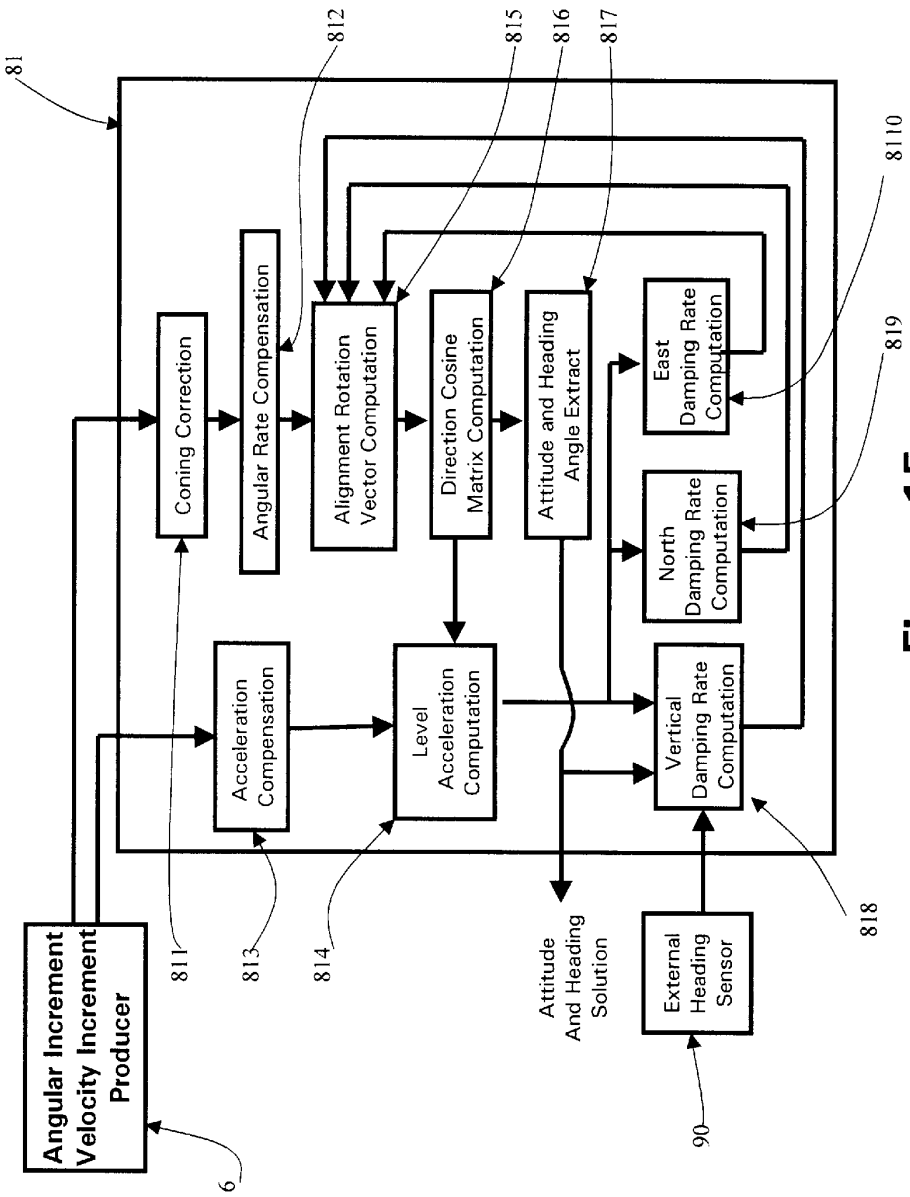

81
812
815
816
817
8110
819
Coning Correction
Angular Rate Compensation
Alignment Rotation Vector Computation
Direction Cosine Matrix Computation
Attitude and Heading Angle Extract
East Damping Rate Computation
North Damping Rate Computation
Acceleration Compensation
Level Acceleration Computation
Vertical Damping Rate Computation
Angular Increment Velocity Increment Producer
6
811
813
814
Attitude And Heading Solution
External Heading Sensor
90
818

Figure 15

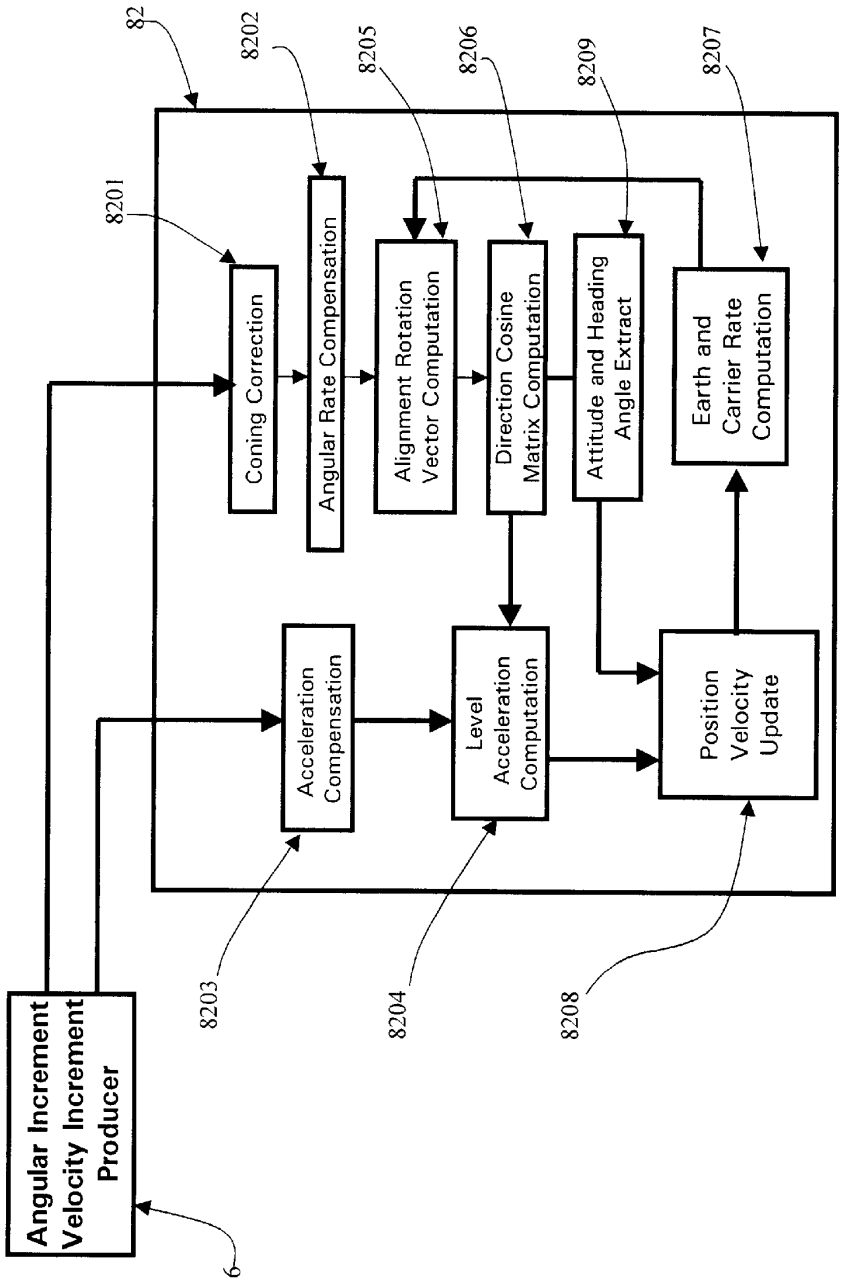

82
8202
8205
8206
8209
8207
8201
Coning Correction
Angular Rate Compensation
Alignment Rotation Vector Computation
Direction Cosine Matrix Computation
Attitude and Heading Angle Extract
Earth and Carrier Rate Computation
Acceleration Compensation
Level Acceleration Computation
Position Velocity Update
8203
8204
8208
Angular Increment Velocity Increment Producer
6

Figure 16

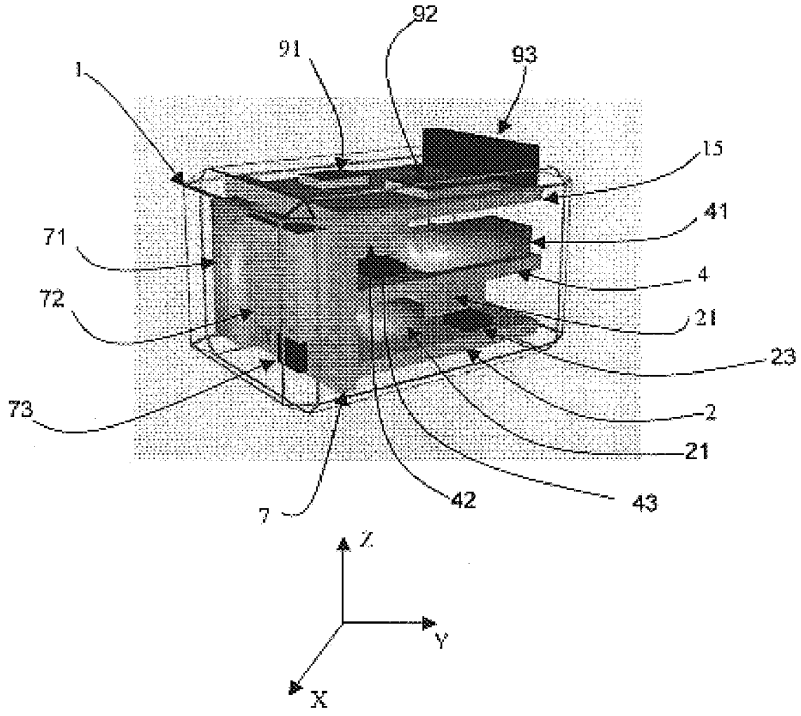


Figure 17

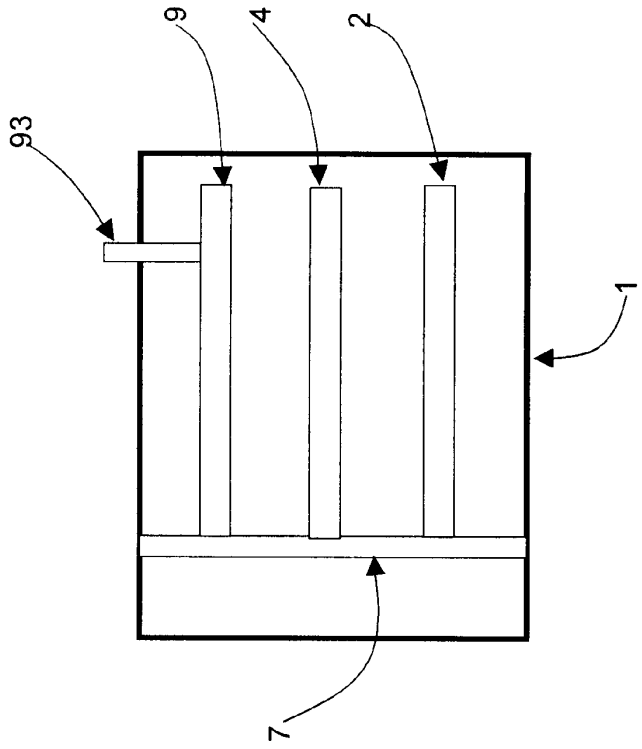


Figure 18

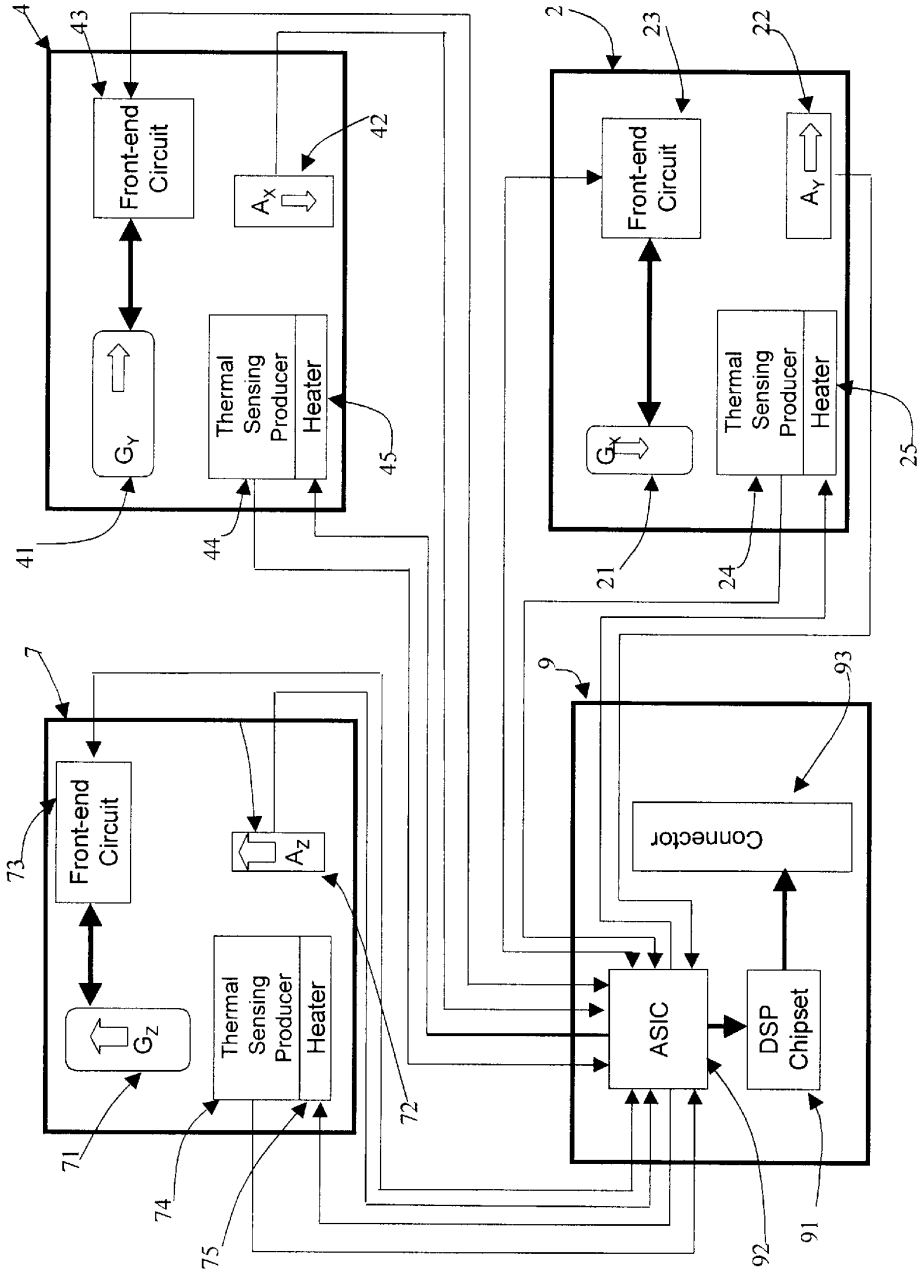

4
43
Front-end Circuit
A_X
42
G_Y
Thermal Sensing Producer
Heater
45
41
44
2
23
22
Front-end Circuit
A_Y
G_X
Thermal Sensing Producer
Heater
25
21
24
7
73
Front-end Circuit
A_Z
G_Z
Thermal Sensing Producer
Heater
71
74
75
72
9
93
Connector
ASIC
DSP Chipset
92
91

Figure 19

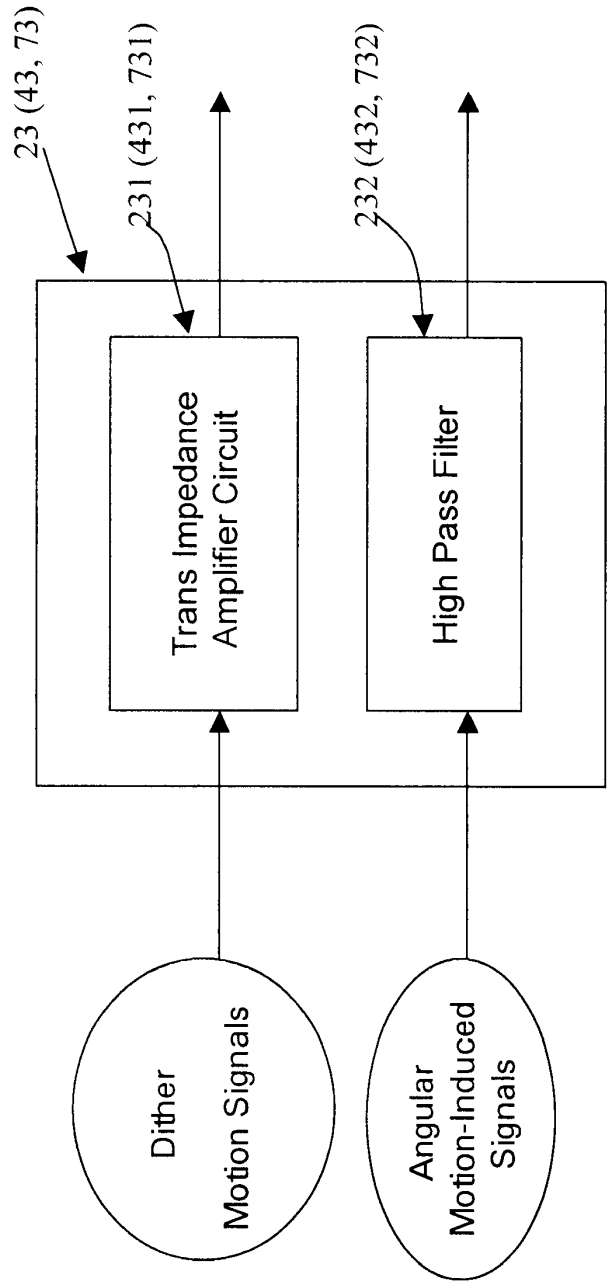

23 (43, 73)
231 (431, 731)
232 (432, 732)
Trans Impedance Amplifier Circuit
High Pass Filter
Dither Motion Signals
Angular Motion-Induced Signals

Figure 20

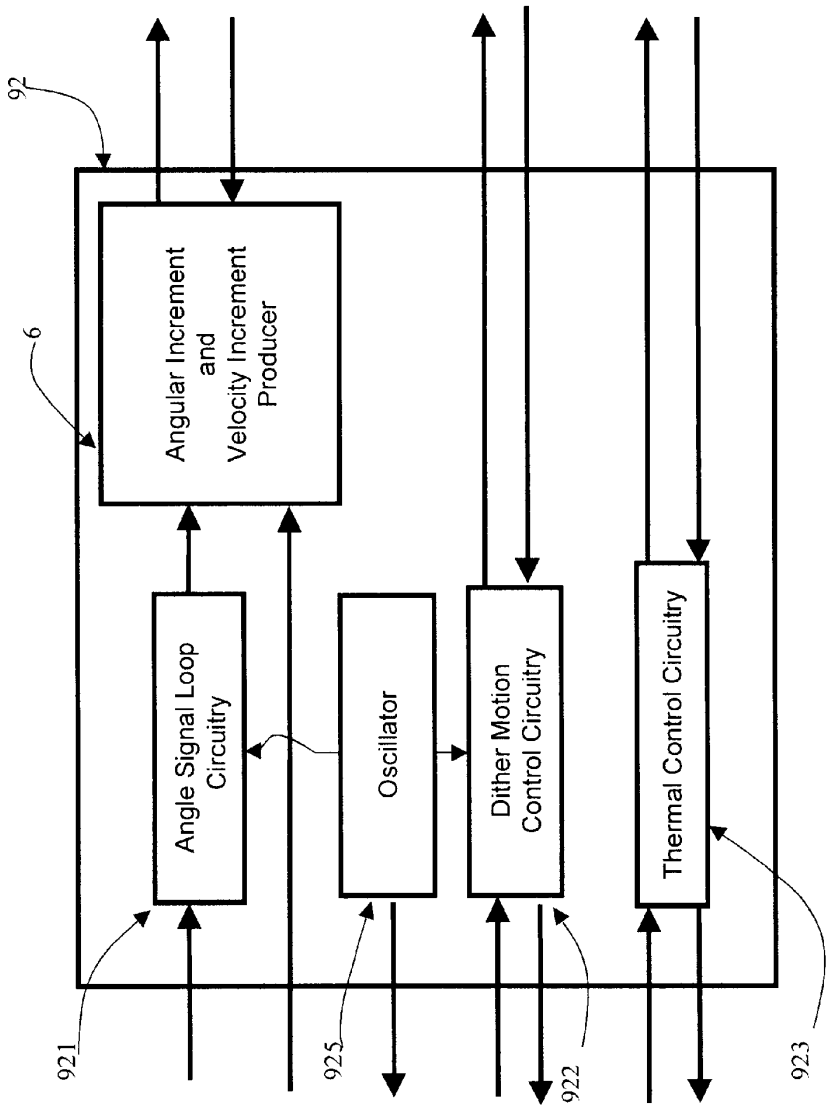

92
6
Angular Increment and Velocity Increment Producer
Angle Signal Loop Circuitry
Oscillator
Dither Motion Control Circuitry
Thermal Control Circuitry
921
925
922
923

Figure 21

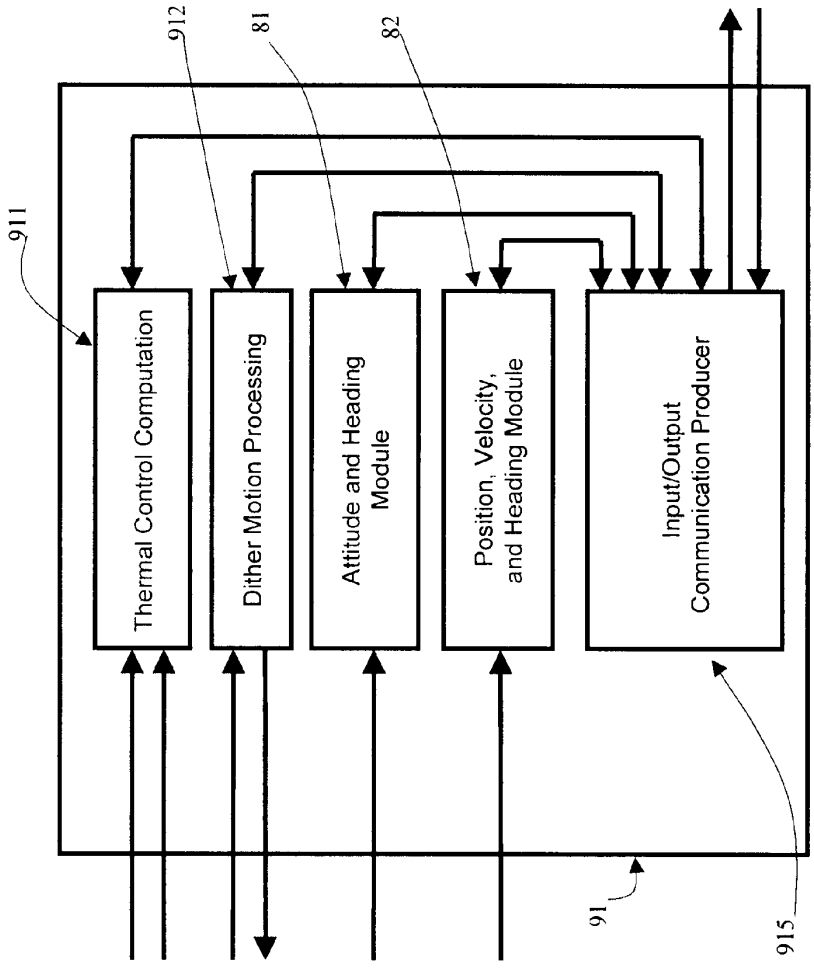

912
81
82
911
Thermal Control Computation
Dither Motion Processing
Attitude and Heading Module
Position, Velocity, and Heading Module
Input/Output Communication Producer
91
915

Figure 22

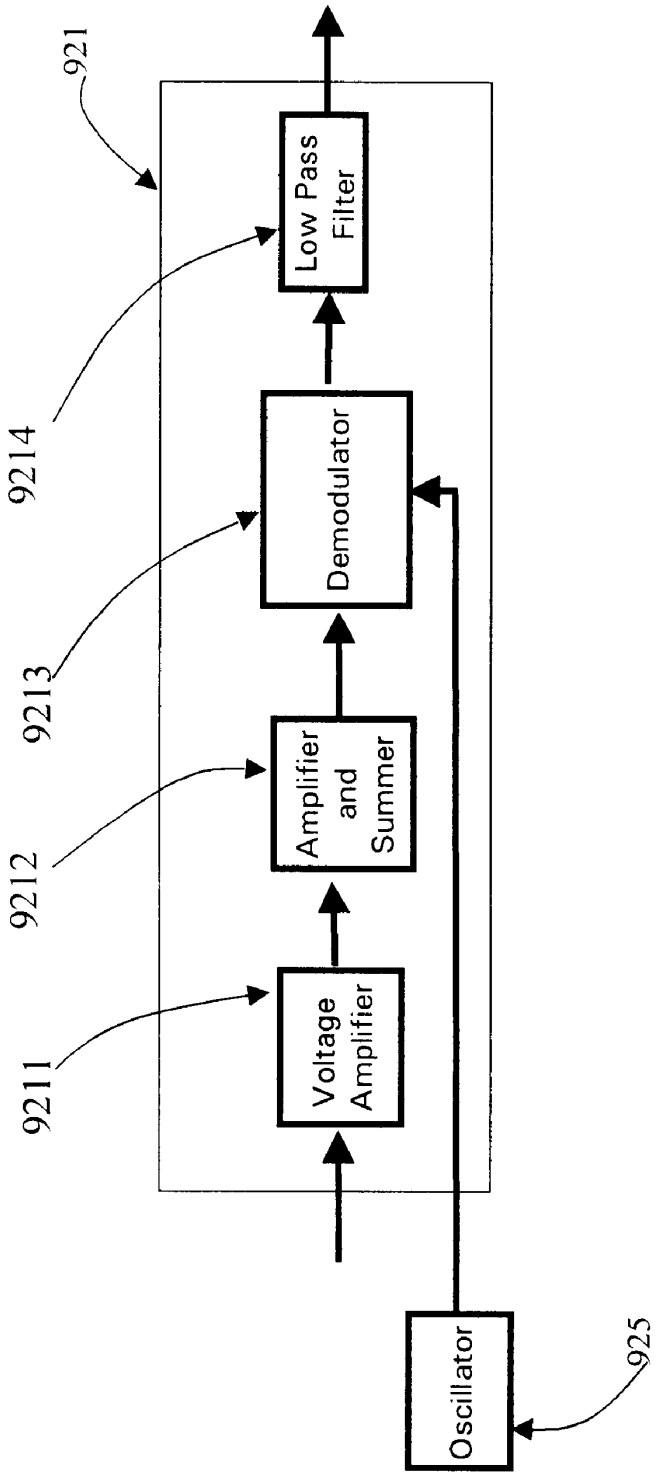

921
Low Pass Filter
9214
Demodulator
9213
Amplifier and Summer
9212
Voltage Amplifier
9211
Oscillator
925

Figure 23

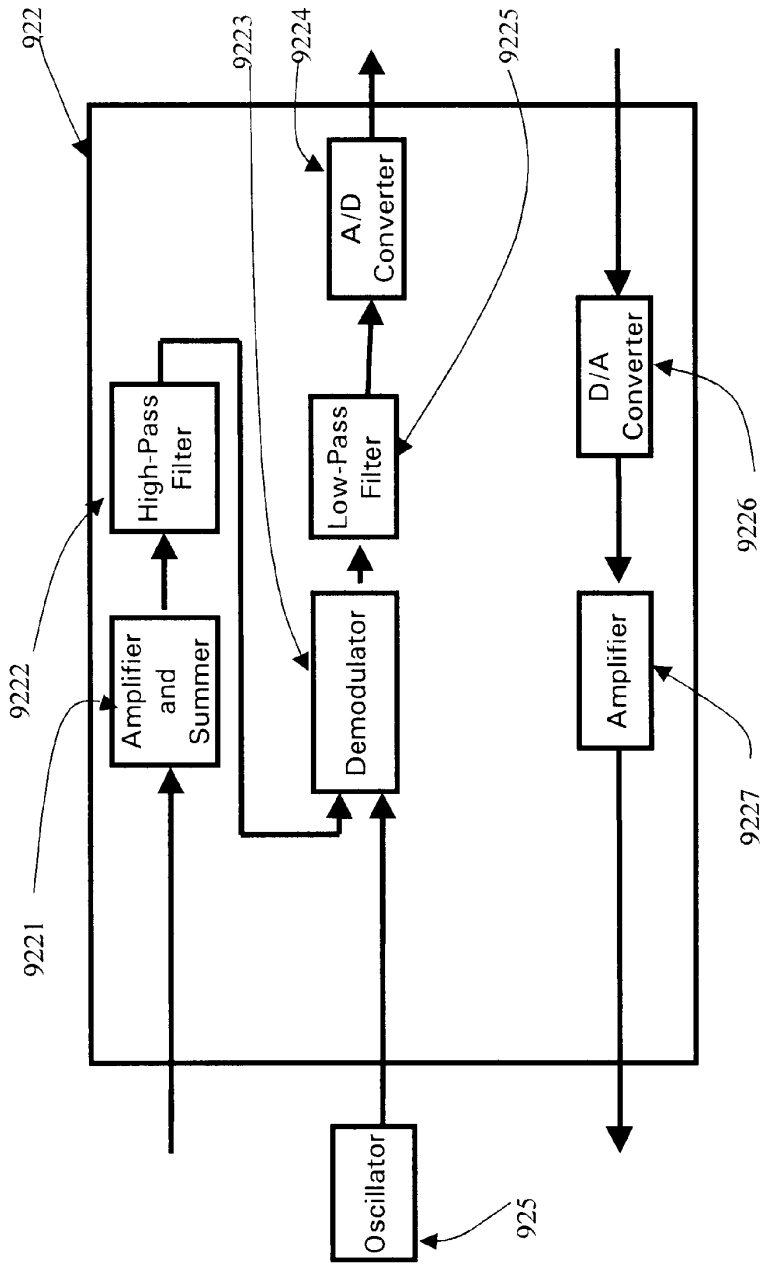

922
9223
9224
9225
A/D Converter
High-Pass Filter
Low-Pass Filter
D/A Converter
9226
9222
Amplifier and Summer
Demodulator
Amplifier
9227
9221
Oscillator
925

Figure 24

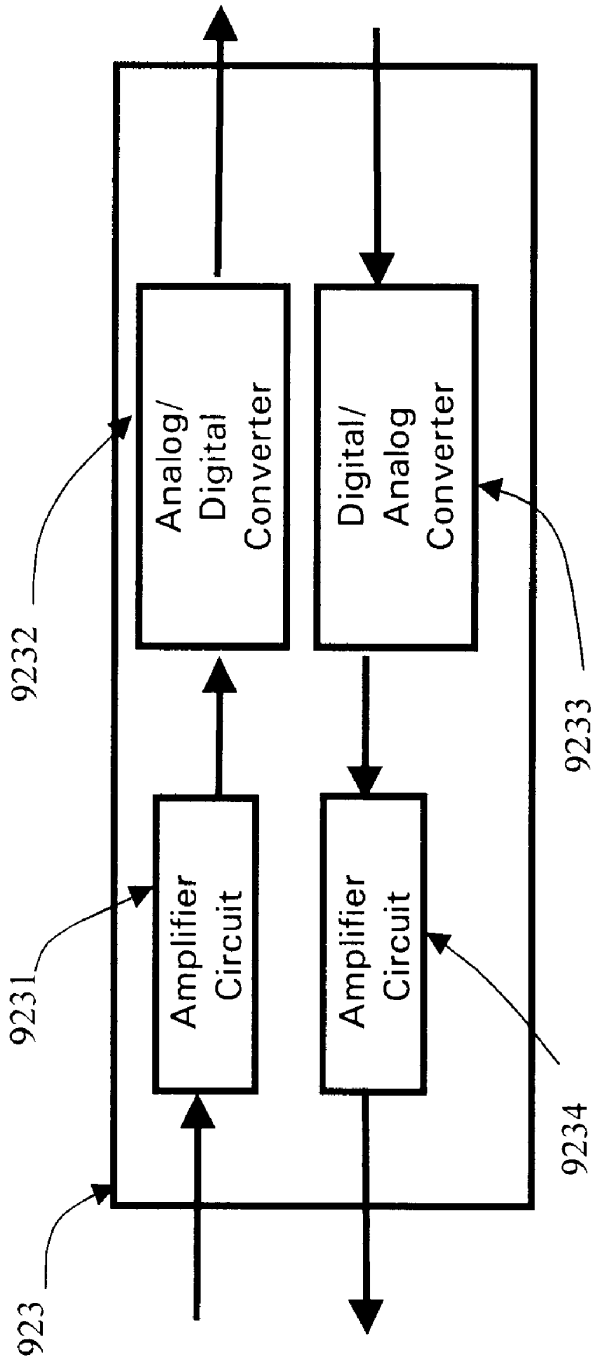

Analog/
Digital
Converter
Digital/
Analog
Converter
Amplifier
Circuit
Amplifier
Circuit
9232
9233
9231
9234
923

Figure 25

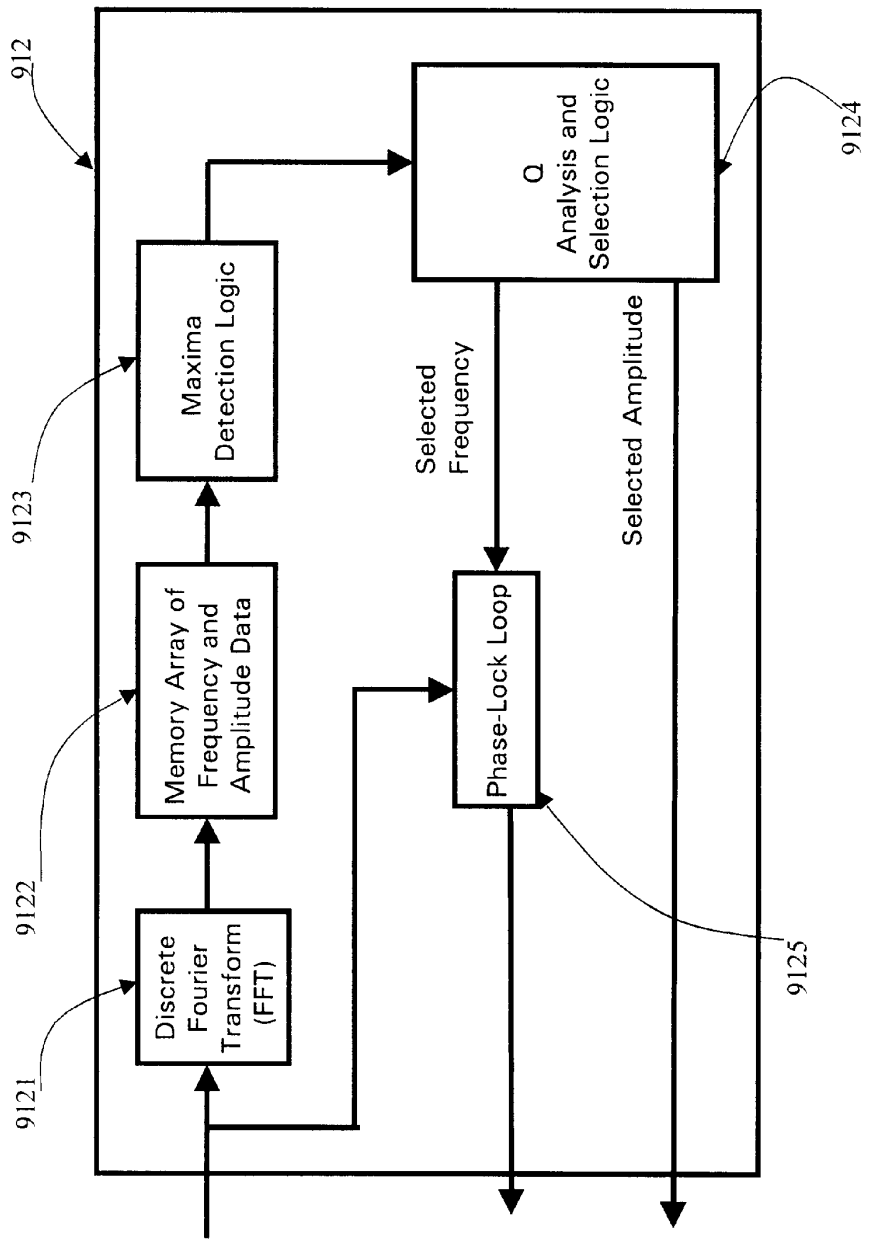

912
9121
9122
9123
9124
9125
Discrete Fourier Transform (FFT)
Memory Array of Frequency and Amplitude Data
Maxima Detection Logic
Q Analysis and Selection Logic
Phase-Lock Loop
Selected Frequency
Selected Amplitude

Figure 26

MICRO INERTIAL MEASUREMENT UNIT

CROSS REFERENCE OF RELATED APPLICATION

This is a divisional application of a non-provisional application having an application Ser. No. 09/477,151 and a filing date of Jan. 4, 2000.

BACKGROUND OF THE PRESENT INVENTION

1. Field of the Present Invention

The present invention relates to motion measurement, and more particularly to a motion inertial measurement unit in micro size that can produce highly accurate, digital angular increments, velocity increments, position, velocity, attitude, and heading measurements of a carrier under dynamic environments.

2. Description of Related Arts

Generally, an inertial measurement unit (IMU) is employed to determine the motion of a carrier. In principle, an inertial measurement unit relies on three orthogonally mounted inertial angular rate producers and three orthogonally mounted acceleration producers to obtain three-axis angular rate and acceleration measurement signals. The three orthogonally mounted inertial angular rate producers and three orthogonally mounted acceleration producers with additional supporting mechanical structure and electronic devices are conventionally called an Inertial Measurement Unit (IMU). The conventional IMUs may be cataloged into Platform IMU and Strapdown IMU.

In the platform IMU, angular rate producers and acceleration producers are installed on a stabilized platform. Attitude measurements can be directly picked off from the platform structure. But attitude rate measurements can not be directly obtained from the platform. Moreover, there are highly accurate feedback control loops associated with the platform.

Compared with the platform IMU, in the strapdown IMU, angular rate producers and acceleration producers are directly strapped down with the carrier and move with the carrier. The output signals of the strapdown rate producers and acceleration producers are expressed in the carrier body frame. The attitude and attitude rate measurements can be obtained by means of a series of computations.

A conventional IMU uses a variety of inertial angular rate producers and acceleration producers. Conventional inertial angular rate producers include iron spinning wheel gyros and optical gyros, such as Floated Integrating Gyros (FIG), Dynamically Tuned Gyros (DTG), Ring Laser Gyros (RLG), Fiber-Optic Gyros (FOG), Electrostatic Gyros (ESG), Josephson Junction Gyros (JJG), Hemisperical Resonating Gyros (HRG), etc. Conventional acceleration producers include Pulsed Integrating Pendulous Accelerometer (PIPA), Pendulous Integrating Gyro Accelerometer (PIGA), etc.

The processing method, mechanical supporting structures, and electronic circuitry of conventional IMUs vary with the type of gyros and accelerometers employed in the IMUs. Because conventional gyros and accelerometers have a large size, high power consumption, and moving mass, complex feedback control loops are required to obtain stable motion measurements. For example, dynamic-tuned gyros and accelerometers need force-rebalance loops to create a moving mass idle position. There are often pulse modulation force-rebalance circuits associated with dynamic-tuned gyros and accelerometer based IMUs. Therefore, conventional IMUs commonly have the following features:

High cost,

Large bulk (volume, mass, large weight),

High power consumption,

Limited lifetime, and

Long turn-on time.

These present deficiencies of conventional IMUs prohibit them from use in the emerging commercial applications, such as phased array antennas for mobile communications, automotive navigation, and handheld equipment.

New horizons are opening up for inertial sensor device technologies. MEMS (MicroElectronicMechanicalSystem) inertial sensors offer tremendous cost, size, and reliability improvements for guidance, navigation, and control systems, compared with conventional inertial sensors.

MEMS, or, as stated more simply, micromachines, are considered as the next logical step in the silicon revolution. It is believed that this coming step will be different, and more important than simply packing more transistors onto silicon. The hallmark of the next thirty years of the silicon revolution will be the incorporation of new types of functionality onto the chip structures, which will enable the chip to, not only think, but to sense, act, and communicate as well.

Prolific MEMS angular rate sensor approaches have been developed to meet the need for inexpensive yet reliable angular rate sensors in fields ranging from automotive to consumer electronics. Single input axis MEMS angular rate sensors are based on either translational resonance, such as tuning forks, or structural mode resonance, such as vibrating rings. Moreover, dual input axis MEMS angular rate sensors may be based on angular resonance of a rotating rigid rotor suspended by torsional springs. Current MEMS angular rate sensors are primarily based on an electronically-driven tuning fork method.

More accurate MEMS accelerometers are the force rebalance type that use closed-loop capacitive sensing and electrostatic forcing. Draper's micromechnical accelerometer is a typical example, where the accelerometer is a monolithic silicon structure consisting of a torsional pendulum with capacitive readout and electrostatic torquer. Analog Device's MEMS accelerometer has an integrated polysilicon capacitive structure fabricated with on-chip BiMOS process to include a precision voltage reference, local oscillators, amplifiers, demodulators, force rebalance loop and self-test functions.

Although the MEMS angular rate sensors and MEMS accelerometers are available commercially and have achieved micro chip-size and low power consumption, however, there is not yet available high performance, small size, and low power consumption IMUs.

SUMMARY OF THE PRESENT INVENTION

A main objective of the present invention is to provide a micro inertial measurement unit, which can produce digital highly accurate angular increment and velocity increment measurements of a carrier from voltage signals output from the specific angular rate and acceleration producers thereof, so as to obtain highly accurate, position, velocity, attitude, and heading measurements of the carrier under dynamic environments.

Another objective of the present invention is to provide a micro inertial measurement unit (IMU) which successfully incorporates the MEMS technology.

Another objective of the present invention is to provide a micro inertial measurement unit, wherein output signals of angular rate producer and acceleration producer are

exploited, and are preferably emerging MEMS (MicroElectronicMechanicalSystem) angular rate sensor arrays and acceleration sensor arrays. These outputs are proportional to rotation and translational motion of the carrier, respectively. Compared with a conventional IMU, the present invention utilizes a feedforward open-loop signal processing scheme to obtain highly accurate motion measurements by means of signal integration, digitizing, temperature control and compensation, sensor error and misalignment calibrations, and dramatically shrinks the size of mechanical and electronic hardware and power consumption, meanwhile, obtains highly accurate motion measurements.

Although the present invention can use existing angular rate devices and acceleration devices, the present invention specifically selects MEMS angular rate devices and acceleration devices to assemble a micro IMU, wherein the micro IMU has the following unique features:

(1) Attitude Heading Reference System (AHRS) Capable Core Sensor Module.

(2) Miniaturized (Length/Width/Height) and Light Weight.

(3) High Performance and Low Cost.

(4) Low Power Dissipation.

(5) Shock resistant and vibration tolerant.

(6) Dramatic Improvement In Reliability (microelectromechanical systems—MEMS).

Another objective of the present invention is to provide a micro IMU rendering into an integrated micro land navigator that has the following unique features:

(1) Miniature, light weight, low power, and low cost.

(2) AHRS, odometer, integrated GPS chipset and flux valve.

(3) Integration filter for sensor data fusion and zero velocity updating.

(4) Typical applications: automobiles, railway vehicles, miniature land vehicles, robots, unmanned ground vehicles, personal navigators, and military land vehicles.

Another objective of the present invention is for the micro IMU to function as aircraft inertial avionics, which has the following unique features:

(1) Rate Gyro

(2) Vertical Gyro

(3) Directional Gyro

(4) AHRS

(5) Inertial Navigation System

(6) Fully-Coupled GPS/MEMS IMU Integrated System

(7) Fully-Coupled GPS/IMU/Radar Altimeter Integrated System

(8) Universal vehicle navigation and control box.

(9) North Finding Module.

Another objective of the present invention is to provide a micro IMU to function as a Spaceborne MEMS IMU Attitude Determination System and a Spaceborne Fully-Coupled GPS/MEMS IMU Integrated system for orbit determination, attitude control, payload pointing, and formation flight, that have the following unique features:

(1) Shock resistant and vibration tolerant

(2) High anti-jamming

(3) High dynamic performance

(4) Broad operating range of temperatures

(5) High resolution

(6) Compact, low power and light weight unit

(7) Flexible hardware and software architecture

Another objective of the present invention is to provide a micro IMU to form a marine INS with embedded GPS, which has the following unique features:

(1) Micro MEMS IMU AHRS with Embedded GPS

(2) Built-in CDU (Control Display Unit)

(3) Optional DGPS (Differential GPS)

(4) Flexible Hardware and Software System Architecture

(5) Low Cost, Light Weight, High Reliability

Another objective of the present invention is to provide a micro IMU to be used in a micro pointing and stabilization mechanism that has the following unique features:

(1) Micro MEMS IMU AHRS utilized for platform stabilization.

(2) MEMS IMU integrated with the electrical and mechanical design of the pointing and stabilization mechanism.

(3) Vehicle motion, vibration, and other interference rejected by a stabilized platform.

(4) Variable pointing angle for tracker implementations.

(5) Typical applications include miniature antenna pointing and tracking control, laser beam pointing for optical communications, telescopic pointing for imaging, airborne laser pointing control for targeting, vehicle control and guidance.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a block diagram illustrating the processing module for a micro inertial measurement unit according to a preferred embodiment of the present invention.

FIG. **2** is a block diagram illustrating the processing modules with thermal control processing for the micro inertial measurement unit according to the above preferred embodiment of the present invention.

FIG. **3** is a block diagram illustrating the processing modules with thermal compensation processing for the micro inertial measurement unit according to the above preferred embodiment of the present invention.

FIG. **4** is a block diagram illustrating an angular increment and velocity increment producer for outputting voltage signals of the angular rate producer and acceleration producer for the micro inertial measurement unit according to the above preferred embodiment of the present invention.

FIG. **5** is a block diagram illustrating another angular increment and velocity increment producer for outputting voltage signals of angular rate producer and acceleration producer for the micro inertial measurement unit according to the above preferred embodiment of the present invention.

FIG. **6** is a block diagram illustrating another angular increment and velocity increment producer for outputting voltage signals of an angular rate producer and acceleration producer for the micro inertial measurement unit according to the above preferred embodiment of the present invention.

FIG. **7** is a block diagram illustrating another angular increment and velocity increment producer for outputting voltage signals of an angular rate producer and acceleration producer for the micro inertial measurement unit according to the above preferred embodiment of the present invention.

FIG. **8** is a block diagram illustrating a thermal processor for outputting analog voltage signals of the thermal sensing producer according to the above preferred embodiment of the present invention.

FIG. **9** is a block diagram illustrating another thermal processor for outputting analog voltage signals of the thermal sensing producer according to the above preferred embodiment of the present invention.

FIG. **10** is a block diagram illustrating another thermal processor for outputting analog voltage signals of the thermal sensing producer according to the above preferred embodiment of the present invention.

FIG. **11** is a block diagram illustrating a processing module for the micro inertial measurement unit according to the above preferred embodiment of the present invention.

FIG. **12** is a block diagram illustrating a temperature digitizer for outputting analog voltage signals of the thermal sensing producer according to the above preferred embodiment of the present invention.

FIG. **13** is a block diagram illustrating a temperature digitizer for outputting analog voltage signals of the thermal sensing producer according to the above preferred embodiment of the present invention.

FIG. **14** is a block diagram illustrating a processing module with thermal compensation processing for the micro inertial measurement unit according to the above preferred embodiment of the present invention.

FIG. **15** is a block diagram illustrating the attitude and heading processing module according to the above preferred embodiment of the present invention.

FIG. **16** is a functional block diagram illustrating the position velocity attitude and heading module according to the above preferred embodiment of the present invention.

FIG. **17** is a perspective view illustrating the inside mechanical structure and circuit board deployment in the micro IMU according to the above preferred embodiment of the present invention.

FIG. **18** is a sectional side view of the micro IMU according to the above preferred embodiment of the present invention.

FIG. **19** is a block diagram illustrating the connection among the four circuit boards inside the micro IMU according to the above preferred embodiment of the present invention.

FIG. **20** is a block diagram of the front-end circuit in each of the first, second, and fourth circuit boards of the micro IMU according to the above preferred embodiment of the present invention.

FIG. **21** is a block diagram of the ASIC chip in the third circuit board of the micro IMU according to the above preferred embodiment of the present invention.

FIG. **22** is a block diagram of processing modules running in the DSP chipset in the third circuit board of the micro IMU according to the above preferred embodiment of the present invention.

FIG. **23** is a block diagram of the angle signal loop circuitry of the ASIC chip in the third circuit board of the micro IMU according to the above preferred embodiment of the present invention.

FIG. **24** is block diagram of the dither motion control circuitry of the ASIC chip in the third circuit board of the micro IMU according to the above preferred embodiment of the present invention.

FIG. **25** is a block diagram of the thermal control circuit of the ASIC chip in the third circuit board of the micro IMU according to the above preferred embodiment of the present invention.

FIG. **26** is a block diagram of the dither motion processing module running in the DSP chipset of the third circuit board of the micro IMU according to the above preferred embodiment of the present invention.

DETAIL DESCRIPTION OF THE PREFERRED EMBODIMENT

Currently, MEMS exploits the existing microelectronics infrastructure to create complex machines with micron feature sizes. These machines can have many functions, including sensing, communication, and actuation. Extensive applications for these devices exist in a wide variety of commercial systems.

The difficulties for building a micro IMU is the achievement of the following hallmark using existing low cost and low accuracy angular rate sensors and accelerometers:

Low cost,
Micro size
Lightweight
Low power consumption
No wear/extended lifetime
Instant turn-on
Large dynamic range
High sensitivity
High stability
High accuracy

To achieve the high degree of performance mentioned above, a number of problems need to be addressed:

(1) Micro-size angular rate sensors and accelerometers need to be obtained. Currently, the best candidate angular rate sensor and accelerometer to meet the micro size are MEMS angular rate sensors and MEMS accelerometers.

(2) Associated mechanical structures need to be designed.

(3) Associated electronic circuitry needs to be designed.

(4) Associated thermal requirements design need to be met to compensate MEMS sensor's thermal effects.

(5) The size and power of the associated electronic circuitry need to be shrunk.

The micro inertial measurement unit of the present invention is preferred to employ with the angular rate producer, such as MEMS angular rate device array or gyro array, that provides three-axis angular rate measurement signals of a carrier, and the acceleration producer, such as MEMS acceleration device array or accelerometer array, that provides three-axis acceleration measurement signals of the carrier, wherein the motion measurements of the carrier, such as attitude and heading angles, are achieved by means of processing procedures of the three-axis angular rate measurement signals from the angular rate producer and the three-axis acceleration measurement signals from the acceleration producer.

In the present invention, output signals of the angular rate producer and acceleration producer are processed to obtain digital highly accurate angular rate increment and velocity increment measurements of the carrier, and are further processed to obtain highly accurate position, velocity, attitude and heading measurements of the carrier under dynamic environments.

Referring to FIG. **1**, the micro inertial measurement unit of the present invention comprises an angular rate producer **5** for producing three-axis (X axis, Y axis and Z axis) angular rate signals; an acceleration producer **10** for producing three-axis (X-axis, Y axis and Z axis) acceleration signals; and an angular increment and velocity increment producer **6** for converting the three-axis angular rate signals

into digital angular increments and for converting the input three-axis acceleration signals into digital velocity increments.

Moreover, a position and attitude processor **80** is adapted to further connect with the micro IMU of the present invention to compute position, attitude and heading angle measurements using the three-axis digital angular increments and three-axis velocity increments to provide a user with a rich motion measurement to meet diverse needs.

The position, attitude and heading processor **80** further comprises two optional running modules:

(1) Attitude and Heading Module **81**, producing attitude and heading angle only; and

(2) Position, Velocity, Attitude, and Heading Module **82**, producing position, velocity, and attitude angles.

In general, the angular rate producer **5** and the acceleration producer **10** are very sensitive to a variety of temperature environments. In order to improve measurement accuracy, referring to FIG. **2**, the present invention further comprises a thermal controlling means for maintaining a predetermined operating temperature of the angular rate producer **5**, the acceleration producer **10** and the angular increment and velocity increment producer **6**. It is worth to mention that if the angular rate producer **5**, the acceleration producer **10** and the angular increment and velocity increment producer **6** are operated in an environment under prefect and constant thermal control, the thermal controlling means can be omitted.

According to the preferred embodiment of the present invention, as shown in FIG. **2**, the thermal controlling means comprises a thermal sensing producer device **15**, a heater device **20** and a thermal processor **30**.

The thermal sensing producer device **15**, which produces temperature signals, is processed in parallel with the angular rate producer **5** and the acceleration producer **10** for maintaining a predetermined operating temperature of the angular rate producer **5** and the acceleration producer **10** and angular increment and velocity increment producer **6** of the micro IMU, wherein the predetermined operating temperature is a constant designated temperature selected between 150° F. and 185° F., preferable 176° F. (±0.1° F.).

The temperature signals produced from the thermal sensing producer device **15** are inputted to the thermal processor **30** for computing temperature control commands using the temperature signals, a temperature scale factor, and a predetermined operating temperature of the angular rate producer **5** and the acceleration producer **10**, and produce driving signals to the heater device **20** using the temperature control commands for controlling the heater device **20** to provide adequate heat for maintaining the predetermined operating temperature in the micro IMU.

Temperature characteristic parameters of the angular rate producer **5** and the acceleration producer **10** can be determined during a series of the angular rate producer and acceleration producer temperature characteristic calibrations.

Referring to FIG. **3**, when the above thermal processor **30** and the heater device **20** are not provided, in order to compensate the angular rate producer and acceleration producer measurement errors induced by a variety of temperature environments, the micro IMU of the present invention can alternatively comprise a temperature digitizer **18** for receiving the temperature signals produced from the thermal sensing producer device **15** and outputting a digital temperature value to the position, attitude, and heading processor **80**. As shown in FIG. **12**, the temperature digitizer **18** can be embodied to comprise an analog/digital converter **182**.

Moreover, the position, attitude, and heading processor **80** is adapted for accessing temperature characteristic parameters of the angular rate producer and the acceleration producer using a current temperature of the angular rate producer and the acceleration producer from the temperature digitizer **18**, and compensating the errors induced by thermal effects in the input digital angular and velocity increments and computing attitude and heading angle measurements using the three-axis digital angular increments and three-axis velocity increments in the attitude and heading processor **80**.

In most applications, the output of the angular rate producer **5** and the acceleration producer **10** are analog voltage signals. The three-axis analog angular rate voltage signals produced from the angular producer **5** are directly proportional to carrier angular rates, and the three-axis analog acceleration voltage signals produced from the acceleration producer **10** are directly proportional to carrier accelerations.

When the outputting analog voltage signals of the angular rate producer **5** and the acceleration producer **10** are too weak for the angular increment and velocity increment producer **6** to read, the angular increment and velocity increment producer **6** may employ amplifying means **660** and **665** for amplifying the analog voltage signals input from the angular rate producer **5** and the acceleration producer **10** and suppress noise signals residing within the analog voltage signals input from the angular rate producer **5** and the acceleration producer **10**, as shown in FIGS. **5** and **6**.

Referring to FIG. **4**, the angular increment and velocity increment producer **6** comprises an angular integrating means **620**, an acceleration integrating means **630**, a resetting means **640**, and an angular increment and velocity increment measurement means **650**.

The angular integrating means **620** and the acceleration integrating means **630** are adapted for respectively integrating the three-axis analog angular rate voltage signals and the three-axis analog acceleration voltage signals for a predetermined time interval to accumulate the three-axis analog angular rate voltage signals and the three-axis analog acceleration voltage signals as an uncompensated three-axis angular increment and an uncompensated three-axis velocity increment for the predetermined time interval to achieve accumulated angular increments and accumulated velocity increments. The integration is performed to remove noise signals that are non-directly proportional to the carrier angular rate and acceleration within the three-axis analog angular rate voltage signals and the three-axis analog acceleration voltage signals, to improve signal-to-noise ratio, and to remove the high frequency signals in the three-axis analog angular rate voltage signals and the three-axis analog acceleration voltage signals. The signals are directly proportional to the carrier angular rate and acceleration within the three-axis analog angular rate voltage signals and the three-axis analog acceleration voltage signals.

The resetting means forms an angular reset voltage pulse and a velocity reset voltage pulse as an angular scale and a velocity scale which are input into the angular integrating means **620** and the acceleration integrating means **630** respectively.

The angular increment and velocity increment measurement means **650** is adapted for measuring the voltage values of the three-axis accumulated angular increments and the three-axis accumulated velocity increments with the angular reset voltage pulse and the velocity reset voltage pulse respectively to acquire angular increment counts and velocity increment counts as a digital form of the angular increment and velocity increment measurements respectively.

In order to output real three-angular increment and velocity increment values as an optional output format to substitute the voltage values of the three-axis accumulated angular increments and velocity increments, the angular increment and velocity increment measurement means **650** also scales the voltage values of the three-axis accumulated angular and velocity increments into real three-axis angular and velocity increment voltage values.

In the angular integrating means **620** and the acceleration integrating means **630**, the three-axis analog angular voltage signals and the three-axis analog acceleration voltage signals are each reset to accumulate from a zero value at an initial point of every predetermined time interval.

As shown in FIG. **6**, in general, the resetting means **640** can be an oscillator **66**, so that the angular reset voltage pulse and the velocity reset voltage pulse are implemented by producing a timing pulse by the oscillator **66**. In applications, the oscillator **66** can be built with circuits, such as Application Specific Integrated Circuits (ASIC) chip and a printed circuit board.

As shown in FIG. **7**, the angular increment and velocity increment measurement means **650**, which is adapted for measuring the voltage values of the three-axis accumulated angular and velocity increments, is embodied as an analog/digital converter **650**. In other words, the analog/digital converter **650** substantially digitizes the raw three-axis angular increment and velocity increment voltage values into digital three-axis angular increment and velocity increments.

Referring to FIGS. **7** and **11**, the amplifying means **660** and **665** of the angular increment and velocity increment producer **6** are embodied by an angular amplifier circuit **61** and an acceleration amplifier circuit **67** respectively to amplify the three-axis analog angular rate voltage signals and the three-axis analog acceleration voltage signals to form amplified three-axis analog angular rate signals and amplified three-axis analog acceleration signals respectively.

The angular integrating means **620** and the acceleration integrating means **630** of the angular increment and velocity increment producer **6** are respectively embodied as an angular integrator circuit **62** and an acceleration integrator circuit **68** for receiving the amplified three-axis analog angular rate signals and the amplified three-axis analog acceleration signals from the angular and acceleration amplifier circuits **61**, **67** which are integrated to form the accumulated angular increments and the accumulated velocity increments respectively.

The analog/digital converter **650** of the angular increment and velocity increment producer **6** further includes an angular analog/digital converter **63**, a velocity analog/digital converter **69** and an input/output interface circuit **65**.

The accumulated angular increments output from the angular integrator circuit **62** and the accumulated velocity increments output from the acceleration integrator circuit are input into the angular analog/digital converter **63** and the velocity analog/digital converter **69** respectively.

The accumulated angular increments are digitized by the angular analog/digital converter **63** by measuring the accumulated angular increments with the angular reset voltage pulse to form digital angular measurements of voltage in terms of the angular increment counts which are output to the input/output interface circuit **65** to generate digital three-axis angular increment voltage values.

The accumulated velocity increments are digitized by the velocity analog/digital converter **69** by measuring the accumulated velocity increments with the velocity reset voltage pulse to form digital velocity measurements of voltage in terms of the velocity increment counts which are output to the input/output interface circuit **65** to generate digital three-axis velocity increment voltage values.

Referring to FIGS. **2** and **8**, in order to achieve flexible adjustment of the thermal processor **30** for the thermal sensing producer device **15** with analog voltage output and the heater device **20** with analog input, the thermal processor **30** can be implemented in a digital feedback controlling loop as shown in FIG. **8**.

The thermal processor **30**, as shown in FIG. **8**, comprises an analog/digital converter **304** connected to the thermal sensing producer device **15**, a digital/analog converter **303** connected to the heater device **20**, and a temperature controller **306** connected with both the analog/digital converter **304** and the digital/analog converter **303**. The analog/digital converter **304** inputs the temperature voltage signals produced by the thermal sensing producer device **15**, wherein the temperature voltage signals are sampled in the analog/digital converter **304** to sampled temperature voltage signals which are further digitized to digital signals and output to the temperature controller **306**.

The temperature controller **306** computes digital temperature commands using the input digital signals from the analog/digital converter **304**, a temperature sensor scale factor, and a pre-determined operating temperature of the angular rate producer and acceleration producer, wherein the digital temperature commands are fed back to the digital/analog converter **303**.

The digital/analog converter **303** converts the digital temperature commands input from the temperature controller **306** into analog signals which are output to the heater device **20** to provide adequate heat for maintaining the predetermined operating temperature of the micro IMU of the present invention.

Moreover, as shown in FIG. **9**, if the voltage signals produced by the thermal sensing producer device **15** are too weak for the analog/digital converter **304** to read, the thermal processor **30** further comprises a first amplifier circuit **301** between the thermal sensing producer device **15** and the digital/analog converter **303**, wherein the voltage signals from the thermal sensing producer device **15** is first input into the first amplifier circuit **301** for amplifying the signals and suppressing the noise residing in the voltage signals and improving the signal-to-noise ratio, wherein the amplified voltage signals are then output to the analog/digital converter **304**.

The heater device **20** requires a specific driving current signal. In this case, referring to FIG. **10**, the thermal processor **30** can further comprise a second amplifier circuit **302** between the digital/analog converter **303** and heater device **20** for amplifying the input analog signals from the digital/analog converter **303** for driving the heater device **20**.

In other words, the digital temperature commands input from the temperature controller **306** are converted in the digital/analog converter **303** into analog signals which are then output to the amplifier circuit **302**.

Referring to FIG. **11**, an input/output interface circuit **305** is required to connect the analog/digital converter **304** and digital/analog converter **303** with the temperature controller **306**. In this case, as shown in FIG. **11**, the voltage signals are sampled in the analog/digital converter **304** to form sampled voltage signals that are digitized into digital signals. The digital signals are output to the input/output interface circuit **305**.

As mentioned above, the temperature controller **306** is adapted to compute the digital temperature commands using

the input digital temperature voltage signals from the input/output interface circuit **305**, the temperature sensor scale factor, and the pre-determined operating temperature of the angular rate producer and acceleration producer, wherein the digital temperature commands are fed back to the input/output interface circuit **305**. Moreover, the digital/analog converter **303** further converts the digital temperature commands input from the input/output interface circuit **305** into analog signals which are output to the heater device **20** to provide adequate heat for maintaining the predetermined operating temperature of the micro IMU.

Referring to FIG. **12**, as mentioned above, the thermal processor **30** and the heater device **20** as disclosed in FIGS. **2**, **8**, **9**, **10**, and **11** can alternatively be replaced by the analog/digital converter **182** connected to the thermal sensing producer device **15** to receive the analog voltage output from the thermal sensing producer device **15**. If the voltage signals produced by the thermal sensing producer device **15** are too weak for the analog/digital converter **182** to read, referring to FIG. **13**, an additional amplifier circuit **181** can be connected between the thermal sensing producer device **15** and the digital/analog converter **182** for amplifying the analog voltage signals and suppressing the noise residing in the voltage signals and improving the voltage signal-to-noise ratio, wherein the amplified voltage signals are output to the analog/digital converter **182** and sampled to form sampled voltage signals that are further digitized in the analog/digital converters **182** to form digital signals connected to the attitude and heading processor **80**.

Alternatively, an input/output interface circuit **183** can be connected between the analog/digital converter **182** and the attitude and heading processor **80**. In this case, referring to FIG. **14**, the input amplified voltage signals are sampled to form sampled voltage signals that are further digitized in the analog/digital converters to form digital signals connected to the input/output interface circuit **183** before inputting into the attitude and heading processor **80**.

Referring to FIG. **1**, the digital three-axis angular increment voltage values or real values and three-axis digital velocity increment voltage values or real values are produced and outputted from the angular increment and velocity increment producer **6**.

In order to adapt to digital three-axis angular increment voltage value and three-axis digital velocity increment voltage values from the angular increment and velocity increment producer **6**, the attitude and heading module **81**, as shown in FIG. **15**, comprises a coning correction module **811**, wherein digital three-axis angular increment voltage values from the input/output interface circuit **65** of the angular increment and velocity increment producer **6** and coarse angular rate bias obtained from an angular rate producer and acceleration producer calibration procedure at a high data rate (short interval) are input into the coning correction module **801**, which computes coning effect errors by using the input digital three-axis angular increment voltage values and coarse angular rate bias, and outputs three-axis coning effect terms and three-axis angular increment voltage values at a reduced data rate (long interval), which are called three-axis long-interval angular increment voltage values.

The attitude and heading module **81** further comprises an angular rate compensation module **812** and an alignment rotation vector computation module **815**. In the angular rate compensation module **812**, the coning effect errors and three-axis long-interval angular increment voltage values from the coning correction module **811** and angular rate device misalignment parameters, fine angular rate bias, angular rate device scale factor, and coning correction scale factor from the angular rate producer and acceleration producer calibration procedure are connected to the angular rate compensation module **812** for compensating definite errors in the three-axis long-interval angular increment voltage values using the coning effect errors, angular rate device misalignment parameters, fine angular rate bias, and coning correction scale factor, and transforming the compensated three-axis long-interval angular increment voltage values to real three-axis long-interval angular increments using the angular rate device scale factor. Moreover, the real three-axis angular increments are output to the alignment rotation vector computation module **815**.

The attitude and heading module **81** further comprises an accelerometer compensation module **813** and a level acceleration computation module **814**, wherein the three-axis velocity increment voltage values from the angular increment and velocity increment producer **6** and acceleration device misalignment, acceleration device bias, and acceleration device scale factor from the angular rate producer and acceleration producer calibration procedure are connected to the accelerometer compensation module **813** for transforming the three-axis velocity increment voltage values into real three-axis velocity increments using the acceleration device scale factor, and compensating the definite errors in three-axis velocity increments using the acceleration device misalignment, accelerometer bias, wherein the compensated three-axis velocity increments are connected to the level acceleration computation module **814**.

By using the compensated three-axis angular increments from the angular rate compensation module **812**, an east damping rate increment from an east damping rate computation module **8110**, a north damping rate increment from a north damping rate computation module **819**, and vertical damping rate increment from a vertical damping rate computation module **818**, a quaternion, which is a vector representing rotation angle of the carrier, is updated, and the updated quaternion is connected to a direction cosine matrix computation module **816** for computing the direction cosine matrix, by using the updated quaternion.

The computed direction cosine matrix is connected to the level acceleration computation module **814** and an attitude and heading angle extract module **817** for extracting attitude and heading angle using the direction cosine matrix from the direction cosine matrix computation module **816**.

The compensated three-axis velocity increments are connected to the level acceleration computation module **814** for computing level velocity increments using the compensated three-axis velocity increments from the acceleration compensation module **814** and the direction cosine matrix from the direction cosine matrix computation module **816**.

The level velocity increments are connected to the east damping rate computation module **8110** for computing east damping rate increments using the north velocity increment of the input level velocity increments from the level acceleration computation module **814**.

The level velocity increments are connected to the north damping rate computation module **819** for computing north damping rate increments using the east velocity increment of the level velocity increments from the level acceleration computation module **814**.

The heading angle from the attitude and heading angle extract module **817** and a measured heading angle from the external heading sensor **90** are connected to the vertical damping rate computation module **818** for computing vertical damping rate increments.

The east damping rate increments, north damping rate increments, and vertical damping rate are fed back to the

alignment rotation vector computation module **815** to damp the drift of errors of the attitude and heading angles.

Alternatively, in order to adapt real digital three-axis angular increment values and real three-axis digital velocity increment values from the angular increment and velocity increment producer **6**, referring to FIG. **15**, the real digital three-axis angular increment values from the angular increment and velocity increment producer **6** and coarse angular rate bias obtained from an angular rate producer and acceleration producer calibration procedure at a high data rate (short interval) are connected to the coning correction module **811** for computing coning effect errors in the coning correction module **811** using the digital three-axis angular increment values and coarse angular rate bias and outputting three-axis coning effect terms and three-axis angular increment values at reduced data rate (long interval), which are called three-axis long-interval angular increment values, into the angular rate compensation module **802**.

The coning effect errors and three-axis long-interval angular increment values from the coning correction module **811** and angular rate device misalignment parameters and fine angular rate bias from the angular rate producer and acceleration producer calibration procedure are connected to the angular rate compensation module **812** for compensating definite errors in the three-axis long-interval angular increment values using the coning effect errors, angular rate device misalignment parameters, fine angular rate bias, and coning correction scale factor, and outputting the real three-axis angular increments to the alignment rotation vector computation module **815**.

The three-axis velocity increment values from the angular increment and velocity increment producer **6** and acceleration device misalignment, and acceleration device bias from the angular rate producer and acceleration producer calibration procedure are connected into the accelerometer compensation module **813** for compensating the definite errors in three-axis velocity increments using the acceleration device misalignment, and accelerometer bias; outputting the compensated three-axis velocity increments to the level acceleration computation module **814**.

It is identical to the above mentioned processing that the following modules use the compensated three-axis angular increments from the angular rate compensation module **812** and compensated three-axis velocity increments from the acceleration compensation module **813** to produce attitude and heading angle.

Referring to FIGS. **3**, **14**, and **15**, which use the temperature compensation method by means of the temperature digitizer **18**, in order to adapt to digital three-axis angular increment voltage value and three-axis digital velocity increment voltage values from the angular increment and velocity increment producer **6**, the digital three-axis angular increment voltage values from the angular increment and velocity increment producer **6** and coarse angular rate bias obtained from an angular rate producer and acceleration producer calibration procedure at a high data rate (short interval) are connected to the coning correction module **811** for computing coning effect errors in the coning correction module **811** using the digital three-axis angular increment voltage values and coarse angular rate bias, and outputting three-axis coning effect terms and three-axis angular increment voltage values at a reduced data rate (long interval), which are called three-axis long-interval angular increment voltage values, into the angular rate compensation module **812**.

The coning effect errors and three-axis long-interval angular increment voltage values from the coning correction module **811** and angular rate device misalignment parameters, fine angular rate bias, angular rate device scale factor, coning correction scale factor from the angular rate producer and acceleration producer calibration procedure, the digital temperature signals from input/output interface circuit **183**, and temperature sensor scale factor are connected to the angular rate compensation module **812** for computing current temperature of the angular rate producer, accessing angular rate producer temperature characteristic parameters using the current temperature of the angular rate producer, compensating definite errors in the three-axis long-interval angular increment voltage values using the coning effect errors, angular rate device misalignment parameters, fine angular rate bias, and coning correction scale factor, transforming the compensated three-axis long-interval angular increment voltage values to real three-axis long-interval angular increments, compensating temperature-induced errors in the real three-axis long-interval angular increments using the angular rate producer temperature characteristic parameters, and outputting the real three-axis angular increments to the alignment rotation vector computation module **805**.

The three-axis velocity increment voltage values from the angular increment and velocity increment producer **6** and acceleration device misalignment, acceleration bias, acceleration device scale factor from the angular rate producer and acceleration producer calibration procedure, the digital temperature signals from the input/output interface circuit **183** of the temperature digitizer **18**, and temperature sensor scale factor are connected to the acceleration compensation module **813** for computing current temperature of the acceleration producer, accessing acceleration producer temperature characteristic parameters using the current temperature of the acceleration producer, transforming the three-axis velocity increment voltage values into real three-axis velocity increments using the acceleration device scale factor, compensating the definite errors in the three-axis velocity increments using the acceleration device misalignment and acceleration bias, compensating temperature-induced errors in the real three-axis velocity increments using the acceleration producer temperature characteristic parameters, and outputting the compensated three-axis velocity increments to the level acceleration computation module **814**.

It is identical to the above mentioned processing that the following modules use the compensated three-axis angular increments from the angular rate compensation module **812** and compensated three-axis velocity increments from the acceleration compensation module **813** to produce the attitude and heading angles.

Alternatively, referring to FIGS. **3**, **14**, and **15**, which use the temperature compensation method, in order to adapt real digital three-axis angular increment values and real three-axis digital velocity increment values from the angular increment and velocity increment producer **6**, the attitude and heading module **81** can be further modified to accept the digital three-axis angular increment values from the angular increment and velocity increment producer **6** and coarse angular rate bias obtained from an angular rate producer and acceleration producer calibration procedure at a high data rate (short interval) into the coning correction module **811** for computing coning effect errors in the coning correction module **811** using the input digital three-axis angular increment values and coarse angular rate bias, and outputting three-axis coning effect data and three-axis angular increment data at a reduced data rate (long interval), which are called three-axis long-interval angular increment values, into the angular rate compensation module **812**.

The coning effect errors and three-axis long-interval angular increment values from the coning correction module

811 and angular rate device misalignment parameters and fine angular rate bias from the angular rate producer and acceleration producer calibration procedure, the digital temperature signals from the input/output interface circuit **183** and temperature sensor scale factor are connected to the angular rate compensation module **812** for computing current temperature of the angular rate producer, accessing angular rate producer temperature characteristic parameters using the current temperature of the angular rate producer, compensating definite errors in the three-axis long-interval angular increment values using the coning effect errors, angular rate device misalignment parameters, fine angular rate bias, and coning correction scale factor, compensating temperature-induced errors in the real three-axis long-interval angular increments using the angular rate producer temperature characteristic parameters, and outputting the real three-axis angular increments to an alignment rotation vector computation module **815**.

The three-axis velocity increment values from the input/output interface circuit **65** and acceleration device misalignment and acceleration bias from the angular rate producer and acceleration producer calibration procedure, the digital temperature signals from the input/output interface circuit **183** and temperature sensor scale factor are input into the acceleration compensation module **803** for computing current temperature of the acceleration producer, accessing the acceleration producer temperature characteristic parameters using the current temperature of the acceleration producer, compensating the definite errors in the three-axis velocity increments using the input acceleration device misalignment, acceleration bias, compensating temperature-induced errors in the real three-axis velocity increments using the acceleration producer temperature characteristic parameters, and outputting the compensated three-axis velocity increments to the level acceleration computation module **804**.

It is identical to the above mentioned processing that the following modules use the compensated three-axis angular increments from the angular rate compensation module **812** and compensated three-axis velocity increments from the acceleration compensation module **813** to produce the attitude and heading angles.

Referring to FIG. **16**, the Position, velocity, and attitude Module **82** comprises:

- a coning correction module **8201**, which is same as the coning correction module **811** of the attitude and heading module **81**;
- an angular rate compensation module **8202**, which is same as the angular rate compensation module **812** of the attitude and heading module **81**;
- an alignment rotation vector computation module **8205**, which is same as the alignment rotation vector computation module **815** of the attitude and heading module **81**;
- a direction cosine matrix computation module **8206**, which is same as the Direction cosine matrix computation module **816** of the attitude and heading module **81**;
- an acceleration compensation module **8203**, which is same as the acceleration compensation module **813** of the attitude and heading module **81**;
- a level acceleration computation module **8204**, which is same as the acceleration compensation module **814** of the attitude and heading module **81**; and
- an attitude and heading angle extract module **8209**, which is same as the attitude and heading angle extract module **817** of the attitude and heading module **81**.

A position and velocity update module **8208** accepts the level velocity increments from the level acceleration computation module **8204** and computes position and velocity solution.

An earth and carrier rate computation module **8207** accepts the position and velocity solution from the position and velocity update module **8208** and computes the rotation rate vector of the local navigation frame (n frame) of the carrier relative to the inertial frame (i frame), which is connected to the alignment rotation vector computation module **8205**.

In order to meet the diverse requirements of application systems, referring to FIGS. **11** and **14**, the digital three-axis angular increment voltage values, the digital three-axis velocity increment, and digital temperature signals in the input/output interface circuit **65** and the input/output interface circuit **305** can be ordered with a specific format required by an external user system, such as RS-232 serial communication standard, RS-422 serial communication standard, the popular PCI/ISA bus standard, and 1553 bus standard, etc.

In order to meet diverse requirements of application systems, referring to FIGS. **1**, **11** and **14**, the digital three-axis angular increment values, the digital three-axis velocity increment, and attitude and heading data in the input/output interface circuit **85** are ordered with a specific format required by an external user system, such as RS-232 serial communication standard, RS-422 serial communication standard, PCI/ISA bus standard, and 1553 bus standard, etc.

As mentioned above, one of the key technologies of the present invention to achieve the micro IMU with a high degree of performance is to utilize a micro size angular rate producer, wherein the micro-size angular rate producer with MEMS technologies and associated mechanical supporting structure and circuitry board deployment of the micro IMU of the present invention are disclosed in the following description.

Another of the key technologies of the present invention to achieve the micro IMU with low power consumption is to design a micro size circuitry with small power consumption, wherein the conventional AISC (Application Specific Integrated Circuit) technologies can be utilized to shrink a complex circuitry into a silicon chip.

Existing MEMS technologies, which are employed into the micro size angular rate producer, use vibrating inertial elements (a micromachine) to sense vehicle angular rate via the Coriolis Effect. The angular rate sensing principle of Coriolis Effect is the inspiration behind the practical vibrating angular rate sensors.

The Coriolis Effect can be explained by saying that when an angular rate is applied to a translating or vibrating inertial element, a Coriolis force is generated. When this angular rate is applied to the axis of an oscillating inertial element, its tines receive a Coriolis force, which then produces torsional forces about the sensor axis. These forces are proportional to the applied angular rate, which then can be measured.

The force (or acceleration), Coriolis force (or Coriolis acceleration) or Coriolis effect, is originally named from a French physicist and mathematician, Gaspard de Coriolis (1792–1843), who postulated his acceleration in 1835 as a correction for the earth's rotation in ballistic trajectory calculations. The Coriolis acceleration acts on a body that is moving around a point with a fixed angular velocity and moving radially as well.

The basic equation defining Coriolis force is expressed as follows:

$$\vec{F}_{Coriolis} = m\vec{a}_{Coriolis} = 2m(\vec{\omega} \times \vec{V}_{Oscillation})$$

where $\vec{F}_{Coriolis}$ is the detected Coriolis force;

m is the mass of the inertial element;

$\vec{a}_{Coriolis}$ is the generated Coriolis acceleration;

$\vec{\omega}$ is the applied (input) angular rotation rate;

$\vec{V}_{Oscillation}$ is the oscillation velocity in a rotating frame.

The Coriolis force produced is proportional to the product of the mass of the inertial element, the input rotation rate, and the oscillation velocity of the inertial element that is perpendicular to the input rotation rate.

The major problems with micromachined vibrating type angular rate producer are insufficient accuracy, sensitivity, and stability. Unlike MEMS acceleration producers that are passive devices, micromachined vibrating type angular rate producer are active devices. Therefore, associated high performance electronics and control should be invented to effectively use hands-on micromachined vibrating type angular rate producers to achieve high performance angular rate measurements in order to meet the requirement of the micro IMU.

Therefore, in order to obtain angular rate sensing signals from a vibrating type angular rate detecting unit, a dither drive signal or energy must be fed first into the vibrating type angular rate detecting unit to drive and maintain the oscillation of the inertial elements with a constant momentum. The performance of the dither drive signals is critical for the whole performance of a MEMS angular rate producer.

As shown in FIG. **17** and FIG. **18**, which are a perspective view and a sectional view of the micro IMU of the present invention as shown in the block diagram of FIG. **1**., the micro IMU comprises a first circuit board **2**, a second circuit board **4**, a third circuit board **7**, and a control circuit board **9** arranged inside a metal cubic case **1**.

The first circuit board **2** is connected with the third circuit board **7** for producing X axis angular sensing signal and Y axis acceleration sensing signal to the control circuit board **9**.

The second circuit board **4** is connected with the third circuit board **7** for producing Y axis angular sensing signal and X axis acceleration sensing signal to the control circuit board **9**.

The third circuit board **7** is connected with the control circuit board **9** for producing Z axis angular sensing signal and Z axis acceleration sensing signals to the control circuit board **9**.

The control circuit board **9** is connected with the first circuit board **2** and then the second circuit board **4** through the third circuit board **7** for processing the X axis, Y axis and Z axis angular sensing signals and the X axis, Y axis and Z axis acceleration sensing signals from the first, second and control circuit board to produce digital angular increments and velocity increments, position, velocity, and attitude solution.

As shown in FIG. **19**, the angular producer **5** of the preferred embodiment of the present invention comprises:

- a X axis vibrating type angular rate detecting unit **21** and a first front-end circuit **23** connected on the first circuit board **2**;
- a Y axis vibrating type angular rate detecting unit **41** and a second front-end circuit **43** connected on the second circuit board **4**;
- a Z axis vibrating type angular rate detecting unit **71** and a third front-end circuit **73** connected on the third circuit board **7**;
- three angular signal loop circuitries **921**, which are provided in a ASIC chip **92** connected on the control circuit board **9**, for the first, second and third circuit boards **2**, **4**, **7** respectively,
- three dither motion control circuitries **922**,which are provided in the ASIC chip **92** connected on the control circuit board **9**, for the first, second and third circuit boards **2**, **4**, **7** respectively;
- an oscillator **925** adapted for providing reference pickoff signals for the X axis vibrating type angular rate detecting unit **21**, the Y axis vibrating type angular rate detecting unit **41**, the Z axis vibrating type angular rate detecting unit **71**, the angle signal loop circuitry **921**, and the dither motion control circuitry **922**; and
- three dither motion processing modules **912**, which run in a DSP (Digital Signal Processor) chipset **91** connected on the control circuit board **9**, for the first, second and third circuit boards **2**, **4**, **7** respectively.

The first, second and third front-end circuits **23**, **43**, **73**, each of which is structurally identical, are used to condition the output signal of the X axis, Y axis and Z axis vibrating type angular rate detecting units **21**, **41**, **71** respectively and each further comprises:

- a trans impedance amplifier circuit **231**, **431**, **731**, which is connected to the respective X axis, Y axis or Z axis vibrating type angular rate detecting unit **21**, **41**, **71** for changing the output impedance of the dither motion signals from a very high level, greater than 100 million ohms, to a low level, less than 100 ohms to achieve two dither displacement signals, which are A/C voltage signals representing the displacement between the inertial elements and the anchor combs. The two dither displacement signals are output to the dither motion control circuitry **922**; and
- a high-pass filter circuit **232**, **432**, **732**, which is connected with the respective X axis, Y axis or Z axis vibrating type angular rate detecting units **21**, **41**, **71** for removing residual dither drive signals and noise from the dither displacement differential signal to form a filtered dither displacement differential signal to the angular signal loop circuitry **921**.

Each of the X axis, Y axis and Z axis angular rate detecting units **21**, **41**, and **71** is structurally identical except that sensing axis of each angular rate detecting unit is placed in an orthogonal direction. The X axis angular rate detecting unit **21** is adapted to detect the angular rate of the vehicle along X axis. The Y axis angular rate detecting unit **21** is adapted to detect the angular rate of the vehicle along Y axis. The Z axis angular rate detecting unit **21** is adapted to detect the angular rate of the vehicle along Z axis.

Each of the X axis, Y axis and Z axis angular rate detecting units **21**, **41** and **71** is a vibratory device, which comprises at least one set of vibrating inertial elements, including tuning forks, and associated supporting structures and means, including capacitive readout means, and uses Coriolis effects to detect vehicle angular rate.

Each of the X axis, Y axis and Z axis vibrating type angular rate detecting units **21**, **41**, **71** receives signals as follows:

1) dither drive signals from the respective dither motion control circuitry **922**, keeping the inertial elements oscillating; and

2) carrier reference oscillation signals from the oscillator **925**, including capacitive pickoff excitation signals.

Each of the X axis, Y axis and Z axis vibrating type angular rate detecting units **21**, **41**, **71** detects the angular motion in X axis, Y axis and Z axis respectively of a vehicle in accordance with the dynamic theory (Coriolis force), and outputs signals as follows:

1) angular motion-induced signals, including rate displacement signals which may be modulated carrier reference oscillation signals to a trans Impedance amplifier circuit **231**, **431**, **731** of the first, second, and third front-end circuit **23**; and

2) its inertial element dither motion signals, including dither displacement signals, to the high-pass filter **232**, **432**, **732** of the first, second, and third front-end circuit **23**.

The three dither motion control circuitries **922** receive the inertial element dither motion signals from the X axis, Y axis and Z axis vibrating type angular rate detecting units **21**, **41**, **71** respectively, reference pickoff signals from the oscillator **925**, and produce digital inertial element displacement signals with known phase.

In order to convert the inertial element dither motion signals from the X axis, Y axis and Z axis vibrating type angular rate detecting units **21**, **41**, **71** to processible inertial element dither motion signals, referring to FIG. **24**, each of the dither motion control circuitries **922** comprises:

an amplifier and summer circuit **9221** connected to the trans impedance amplifier circuit **231**, **431**, **731** of the respective first, second or third front-end circuit **23**, **43**, **73** for amplifying the two dither displacement signals for more than ten times and enhancing the sensitivity for combining the two dither displacement signals to achieve a dither displacement differential signal by subtracting a center anchor comb signal with a side anchor comb signal;

a high-pass filter circuit **9222** connected to the amplifier and summer circuit **9221** for removing residual dither drive signals and noise from the dither displacement differential signal to form a filtered dither displacement differential signal;

a demodulator circuit **9223** connected to the high-pass filter circuit **2225** for receiving the capacitive pickoff excitation signals as phase reference signals from the oscillator **925** and the filtered dither displacement differential signal from the high-pass filter **9222** and extracting the in-phase portion of the filtered dither displacement differential signal to produce an inertial element displacement signal with known phase;

a low-pass filter **9225** connected to the demodulator circuit **9223** for removing high frequency noise from the inertial element displacement signal input thereto to form a low frequency inertial element displacement signal;

an analog/digital converter **9224** connected to the low-pass filter **9225** for converting the low frequency inertial element displacement analog signal to produce a digitized low frequency inertial element displacement signal to the dither motion processing module **912** (disclosed in the following text) running the DSP chipset **91**;

a digital/analog converter **9226** processing the selected amplitude from the dither motion processing module **912** to form a dither drive signal with the correct amplitude; and

an amplifier **9227** which generates and amplifies the dither drive signal to the respective X axis, Y axis or Z axis vibrating type angular rate detecting unit **21**, **41**, **71** based on the dither drive signal with the selected frequency and correct amplitude.

The oscillation of the inertial elements residing inside each of the X axis, Y axis and Z axis vibrating type angular rate detecting units **21**, **41**, **71** is generally driven by a high frequency sinusoidal signal with precise amplitude. It is critical to provide the X axis, Y axis and Z axis vibrating type angular rate detecting units **21**, **41**, **71** with high performance dither drive signals to achieve keen sensitivity and stability of X-axis, Y-axis and Z axis angular rate measurements.

The dither motion processing module **912** receives digital inertial element displacement signals with known phase from the analog/digital converter **9224** of the dither motion control circuitry **922** for:

(1) finding the frequencies which have the highest Quality Factor (Q) Values,

(2) locking the frequency, and

(3) locking the amplitude to produce a dither drive signal, including high frequency sinusoidal signals with a precise amplitude, to the respective X axis, Y axis or Z axis vibrating type angular rate detecting unit **21**, **41**, **71** to keep the inertial elements oscillating at the predetermined resonant frequency.

The three dither motion processing modules **912** is to search and lock the vibrating frequency and amplitude of the inertial elements of the respective X axis, Y axis or Z axis vibrating type angular rate detecting unit **21**, **41**, **71**. Therefore, the digitized low frequency inertial element displacement signal is first represented in terms of its spectral content by using discrete Fast Fourier Transform (FFT).

Discrete Fast Fourier Transform (FFT) is an efficient algorithm for computing discrete Fourier transform (DFT), which dramatically reduces the computation load imposed by the DFT. The DFT is used to approximate the Fourier transform of a discrete signal. The Fourier transform, or spectrum, of a continuous signal is defined as:

$$X(j\omega) = \int_{-\infty}^{\infty} x(t)e^{-j\omega t}\,dt$$

The DFT of N samples of a discrete signals X(nT) is given by:

$$X_s(k\omega) = \sum_{n=0}^{N-1} x(nT)e^{-jk\omega Tnk}$$

where $\omega=2\pi/NT$, T is the inter-sample time interval. The basic property of FFT is its ability to distinguish waves of different frequencies that have been additively combined.

After the digitized low frequency inertial element displacement signals are represented in terms of their spectral content by using discrete Fast Fourier Transform (FFT), Q (Quality Factor) Analysis is applied to their spectral content to determine the frequency with global maximal Q value. The vibration of the inertial elements of the respective X axis, Y axis or Z axis vibrating type angular rate detecting unit **21**, **41**, **71** at the frequency with global maximal Q value can result in minimal power consumption and cancel many of the terms that affect the excited mode. The Q value is a function of basic geometry, material properties, and ambient operating conditions.

A phase-locked loop and digital/analog converter is further used to control and stabilize the selected frequency and amplitude.

Referring to FIG. **26**, the dither motion processing module **912** further includes a discrete Fast Fourier Transform (FFT) module **9121**, a memory array of frequency and amplitude data module **9122**, a maxima detection logic module **9123**, and a Q analysis and selection logic module **9124** to find the frequencies which have the highest Quality Factor (Q) Values.

The discrete Fast Fourier Transform (FFT) module **9121** is arranged for transforming the digitized low frequency inertial element displacement signal from the analog/digital converter **9224** of the dither motion control circuitry **922** to form amplitude data with the frequency spectrum of the input inertial element displacement signal.

The memory array of frequency and amplitude data module **9122** receives the amplitude data with frequency spectrum to form an array of amplitude data with frequency spectrum.

The maxima detection logic module **9123** is adapted for partitioning the frequency spectrum from the array of the amplitude data with frequency into plural spectrum segments, and choosing those frequencies with the largest amplitudes in the local segments of the frequency spectrum.

The Q analysis and selection logic module **9124** is adapted for performing Q analysis on the chosen frequencies to select frequency and amplitude by computing the ratio of amplitude/bandwidth, wherein the range for computing bandwidth is between +−½ of the peek for each maximum frequency point.

Moreover, the dither motion processing module **912** further includes a phase-lock loop **9125** to reject noise of the selected frequency to form a dither drive signal with the selected frequency, which serves as a very narrow bandpass filter, locking the frequency.

The three angle signal loop circuitries **921** receive the angular motion-induced signals from the X axis, Y axis and Z axis vibrating type angular rate detecting units **21**, **41**, **71** respectively, reference pickoff signals from the oscillator **925**, and transform the angular motion-induced signals into angular rate signals. Referring to FIG. **23**, each of the angle signal loop circuitries **921** for the respective first, second or third circuit board **2**, **4**, **7** comprises:

- a voltage amplifier circuit **9211**, which amplifies the filtered angular motion-induced signals from the high-pass filter circuit **232** of the respective first, second or third front-end circuit **23**, **43**, **73** to an extent of at least 100 milivolts to form amplified angular motion-induced signals;
- an amplifier and summer circuit **9212**, which subtracts the difference between the angle rates of the amplified angular motion-induced signals to produce a differential angle rate signal;
- a demodulator **9213**, which is connected to the amplifier and summer circuit **9212**, extracting the amplitude of the in-phase differential angle rate signal from the differential angle rate signal and the capacitive pickoff excitation signals from the oscillator **925**;
- a low-pass filter **9214**, which is connected to the demodulator **9213**, removing the high frequency noise of the amplitude signal of the in-phase differential angle rate signal to form the angular rate signal output to the angular increment and velocity increment producer **6**.

Referring to FIGS. **17** to **19**, the acceleration producer **10** of the preferred embodiment of the present invention comprises:

- a X axis accelerometer **42**, which is provided on the second circuit board **4** and connected with the angular increment and velocity increment producer **6** provided in the AISC chip **92** of the control circuit board **9**;
- a Y axis accelerometer **22**, which is provided on the first circuit board **2** and connected with angular increment and velocity increment producer **6** provided in the AISC chip **92** of the control circuit board **9**; and
- a Z axis accelerometer **72**, which is provided on the third circuit board **7** and connected with angular increment and velocity increment producer **6** provided in the AISC chip **92** of the control circuit board **9**.

Referring to FIGS. **2**, **18** and FIG. **19**, thermal sensing producer device **15** of the preferred embodiment of the present invention further comprises:

- a first thermal sensing producing unit **24** for sensing the temperature of the X axis angular rate detecting unit **21** and the Y axis accelerometer **22**;
- a second thermal sensing producer **44** for sensing the temperature of the Y axis angular rate detecting unit **41** and the X axis accelerometer **42**; and
- a third thermal sensing producer **74** for sensing the temperature of the Z axis angular rate detecting unit **71** and the Z axis accelerometer **72**.

Referring to FIGS. **2** and **19**, the heater device **20** of the preferred embodiment of the present invention further comprises:

- a first heater **25**, which is connected to the X axis angular rate detecting unit **21**, the Y axis accelerometer **22**, and the first front-end circuit **23**, for maintaining the predetermined operational temperature of the X axis angular rate detecting unit **21**, the Y axis accelerometer **22**, and the first front-end circuit **23**;
- a second heater **45**, which is connected to the Y axis angular rate detecting unit **41**, the X axis accelerometer **42**, and the second front-end circuit **43**, for maintaining the predetermined operational temperature of the X axis angular rate detecting unit **41**, the X axis accelerometer **42**, and the second front-end circuit **43**; and
- a third heater **75**, which is connected to the Z axis angular rate detecting unit **71**, the Z axis accelerometer **72**, and the third front-end circuit **73**, for maintaining the predetermined operational temperature of the Z axis angular rate detecting unit **71**, the Z axis accelerometer **72**, and the third front-end circuit **73**.

Referred to FIGS. **2**, **18**, **19**, **21**, and **25**, the thermal processor **30** of the preferred embodiment of the present invention further comprises three identical thermal control circuitries **923** and the thermal control computation modules **911** running the DSP chipset **91**.

As shown in FIGS. **19** and **25**, each of the thermal control circuitries **923** further comprises:

- a first amplifier circuit **9231**, which is connected with the respective X axis, Y axis or Z axis thermal sensing producer **24**, **44**, **74**, for amplifying the signals and suppressing the noise residing in the temperature voltage signals from the respective X axis, Y axis or Z axis thermal sensing producer **24**, **44**, **74** and improving the signal-to-noise ratio;
- an analog/digital converter **9232**, which is connected with the amplifier circuit **9231**, for sampling the temperature voltage signals and digitizing the sampled temperature voltage signals to digital signals, which are output to the thermal control computation module **911**;
- a digital/analog converter **9233** which converts the digital temperature commands input from the thermal control computation module **911** into analog signals; and

a second amplifier circuit **9234**, which receives the analog signals from the digital/analog converter **9233**, amplifying the input analog signals from the digital/analog converter **9233** for driving the respective first, second or third heater **25**, **45**, **75**; and closing the temperature controlling loop.

The thermal control computation module **911** computes digital temperature commands using the digital temperature voltage signals from the analog/digital converter **9232**, the temperature sensor scale factor, and the predetermined operating temperature of the angular rate producer and acceleration producer, wherein the digital temperature commands are connected to the digital/analog converter **9233**.

In order to achieve a high degree of fall functional performance for the micro IMU, a specific package of the first circuit board **2**, the second circuit board **4**, the third circuit board **7**, and the control circuit board **9** of the preferred embodiment of the present invention is provided and disclosed as follows:

In the preferred embodiment of the present invention, as shown in FIGS. **17**, **18**, and **19**, the third circuit board **7** is bonded to a supporting structure by means of a conductive epoxy, and the first circuit board **2**, the second circuit board **4**, and the control circuit board **9** are arranged parallelly to bond to the third circuit board **7** perpendicularly by a non conductive epoxy.

In other words, the first circuit board **2**, the second circuit board **4**, and the control circuit board **9** are soldered to the third circuit board **7** in such a way as to use the third circuit board **7** as an interconnect board, thereby avoiding the necessity to provide interconnect wiring, so as to minimize the small size.

The first, second, third, and control circuit boards **2**, **4**, **7**, and **9** are constructed using ground planes which are brought out to the perimeter of each circuit board **2**, **4**, **7**, **9**, so that the conductive epoxy can form a continuous ground plane with the supporting structure. In this way the electrical noise levels are minimized and the thermal gradients are reduced. Moreover, the bonding process also reduces the change in misalignments due to structural bending caused by acceleration of the IMU.

What is claimed is:

1. A micro inertial measurement unit, comprising:

an angular rate producer comprising a X axis angular rate detecting unit which produces a X axis angular rate electrical signal, a Y axis angular rate detecting unit which produces a Y axis angular rate electrical signal, and a Z axis angular rate detecting unit which produces a Z axis angular rate electrical signal;

an acceleration producer comprising a X axis accelerometer which produces a X axis acceleration electrical signal, a Y axis accelerometer which produces a Y axis acceleration electrical signal, and a Z axis accelerometer which produces a Z axis acceleration electrical signal; and

an angular increment and velocity increment producer, which is electrically connected with said X axis, Y axis and Z axis angular rate detecting units and said X axis, Y axis and Z axis accelerometers, receiving said X axis, Y axis and Z axis angular rate electrical signals and said X axis, Y axis and Z axis acceleration electrical signals from said angular rate producer and said acceleration producer respectively, wherein said X axis, Y axis and Z axis angular rate electrical signals and said X axis, Y axis and Z axis acceleration electrical signals are converted into are digital angular increments and digital velocity increments respectively.

2. The micro inertial measurement unit, as recited in claim **1**, further comprising a thermal controlling means for maintaining a predetermined operating temperature of said angular rate producer, said acceleration producer and said angular increment and velocity increment producer.

3. A micro inertial measurement unit, as recited in claim **2**, wherein said X axis, Y axis and Z axis angular rate electrical signals produced from said angular producer are analog angular rate voltage signals directly proportional to angular rates of a carrier carrying said micro inertial measurement unit, and said X axis, Y axis and Z axis acceleration electrical signals produced from said acceleration producer are analog acceleration voltage signals directly proportional to accelerations of said vehicle.

4. A micro inertial measurement unit, as recited in claim **1**, wherein said X axis, Y axis and Z axis angular rate electrical signals produced from said angular producer are analog angular rate voltage signals directly proportional to angular rates of a carrier carrying said micro inertial measurement unit, and said X axis, Y axis and Z axis acceleration electrical signals produced from said acceleration producer are analog acceleration voltage signals directly proportional to accelerations of said vehicle.

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