SOLID STATE STRAP DOWN VERTICAL GYRO SYSTEM

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INTRODUCTION

Watson Industries, Inc. is in its fifteenth year of operation and has provided sensors for a wide range of projects, including stabilization, control and instrumentation for military and civilian projects worldwide. These projects are often concerned with sensing vehicle attitude. Because of this, the product line of Watson Industries. centers on sensors and especially on solid state rate gyros.

The philosophy for the development of technology at Watson Industries has always been that sensors need to be solid state, low cost and microprocessor-based to compete in the modern market. The custom products at Watson Industries have led to the development of a special form of vertical gyro which has broad applications and which is especially appropriate for remote piloted vehicle systems.

VERTICAL GYRO SYSTEMS

The traditional vertical gyro is a spinning wheel in a gimbaled frame, as shown in Figure 1. This traditional system uses torquers at each gimbal to adjust and correct the attitude. Pendulum devices are used in initialization to erect the gyro and, during operation, to remove accumulated errors. Such systems are usually limited in erection rate to control responses to spurious disturbances and the erection rate is often made variable to improve initialization time. Systems like this become complex and, because they are mechanically based, are expensive and prone to wear and failure.

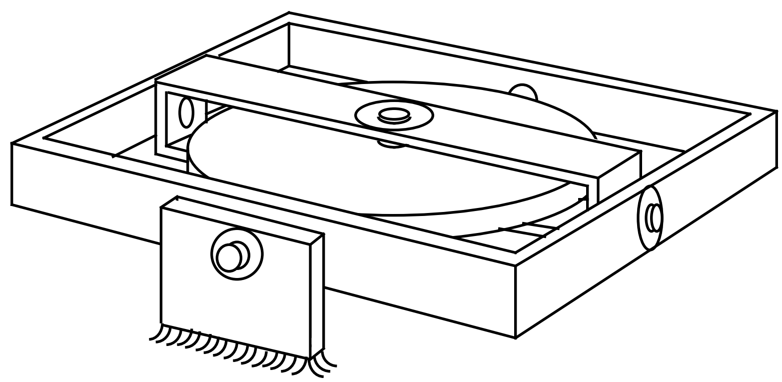


Figure 1. Traditional Vertical Gyro.

A simplified block diagram of the closed-loop system is shown in Figure 2. This represents a traditional gyro. The torque correction is applied as an angular rate to the system (as shown in the diagram). The rate of closure gives rise to a natural frequency w.

The diagram does not show the phasing of the reference or the torquer. These are off-set by 90° to compensate for precession in the system.

The diagram also does not show the limiting of the error signal (the output angle minus the reference). It is typical to limit this error to about ±10°.

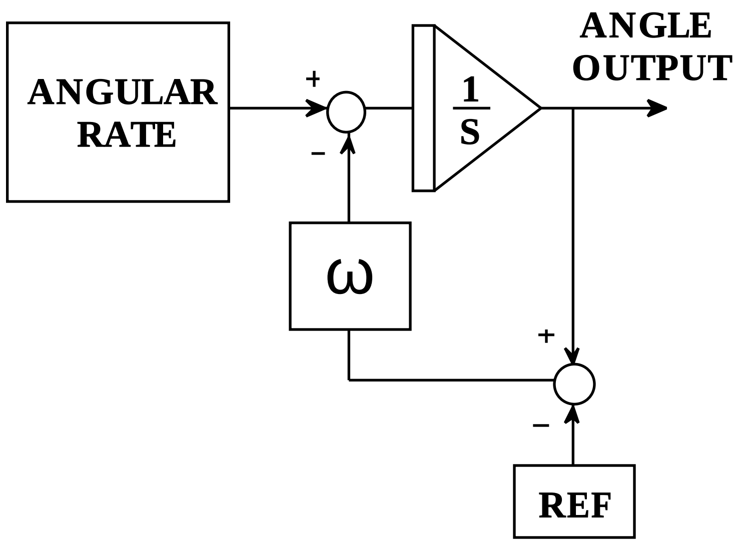


Figure 2. Gyro Torque Loop.

Figure 3 is a graph that shows the relationship between the gyro performance, the reference source and how they meet at the natural frequency w. This variable, w, is the inverse of the time constant to the system.

The upper limit of the system time constant is bounded by the spin of the Earth, the size of gyro errors to be overcome and the accuracy required of the gyro. Earth rotation is at the rate of 15°/hour. If an accuracy of 1° is required of the gyro, then a time constant for the system must be less than 4 minutes. Another reason to use a lower time constant comes from the need to quickly remove errors that may be generated by complex dynamic motions of the gyro. On the other hand, the need to average out errors from centrifugal force and acceleration demand a high time constant. The effects from centrifugal force and acceleration can also be rejected by disabling the torquer loop during maneuvers.

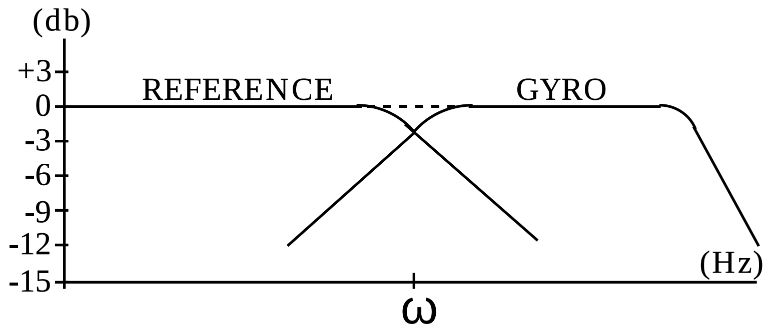


Figure 3. Gyro Spectral Distribution.

The technical limitations of such mechanical gyros include gimbal lock, initialization time and reliability. Gimbal lock is a technical problem that comes from the fact that, at high angles of vertical alignment, at zenith and nadir in pointing, the spin axis of the gyro and the roll axis of the gyro coincide, creating a tumbling effect as friction drags the roll axis along with the spin. Most gyros are limited to a range of +80 degrees to -80 degrees in elevation to mitigate this problem.

The initialization time comes from the inertia of the system and the need for the wheel to spin up and from the limited torque available in the torquing system to erect the gyro.

Reliability problems come, of course, from the mechanical parts and the wearing surfaces involved in a gyro system.

STRAP DOWN SYSTEM

What is proposed to replace this traditional gyro system is a solid-state, strap down system that is, by nature, more electronic than mechanical. The objectives are to reduce cost and to increase reliability. This also gives more flexibility to the design as the design becomes modified through software rather than through physical reconfiguration. The basis for such a system would be mathematical transforms, in this case the transform converting body axes to Euler angles (earth coordinates) uses a quaternion matrix. This is very similar to Watson Industries' AHRS-C303 which is in current production. The main differences are the use of upgraded solid state rate gyros and conversion to a wider operating temperature range.

The standard terminology for the axes for linear and rotational motions are shown in Figure 4. These same axes are related in Figure 5 to earth coordinates. This is a convenient coordinate system as it matches the type of system used in the displays of commercial aircraft.

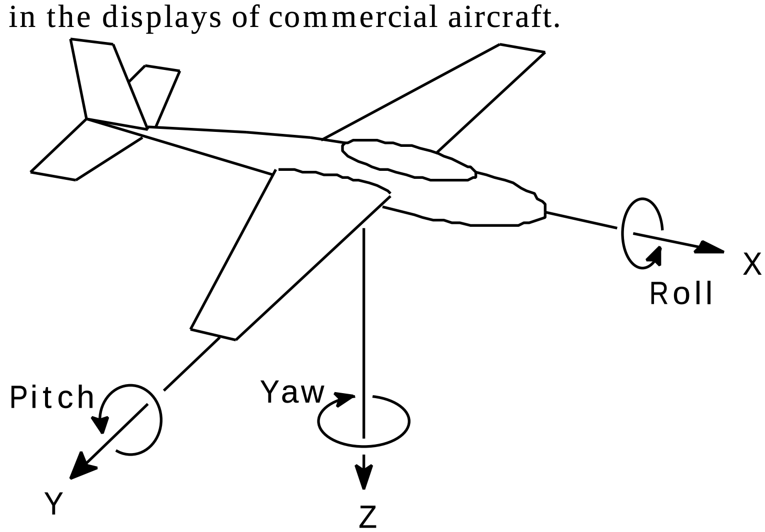


Figure 4. Body Axis Definitions.

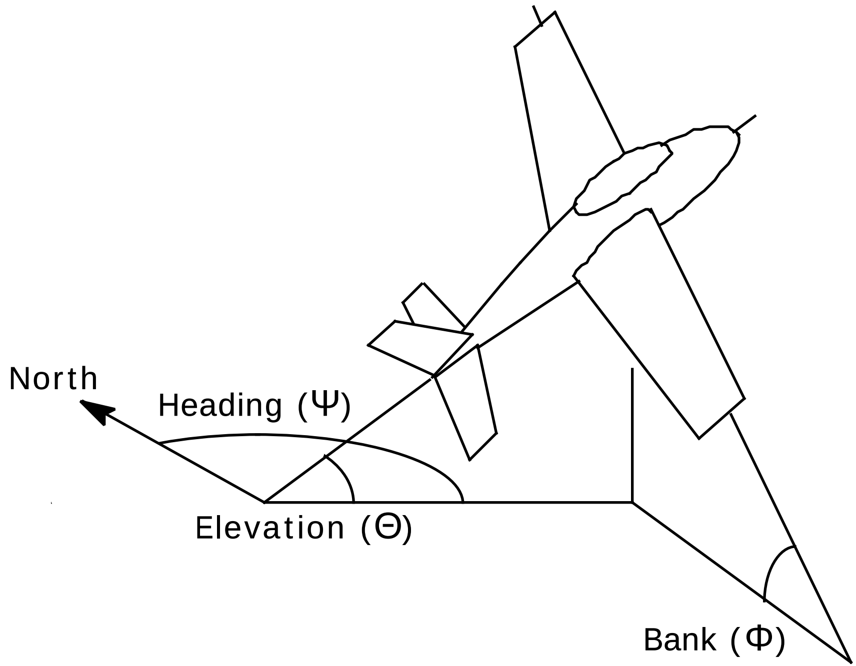


Figure 5. Earth Referenced Axis Definitions.

The basis of the equations used are the linear transforms, as shown in the equations below. These equations deal with linear vectors rather than angular rates.

Linear Vector Transform Equations

X', Y', Z' are the new vector components of the vector X, Y, Z rotated by Φ, Θ, Ψ: [1]

$$X' = X(\cos\Theta \cos\Psi) + Y(\sin\Phi \sin\Theta \cos\Psi - \cos\Phi \sin\Psi) + Z(\cos\Phi \sin\Theta \cos\Psi + \sin\Phi \sin\Psi)$$

$$Y' = X(\cos\Theta \sin\Psi) + Y(\sin\Phi \sin\Theta \sin\Psi + \cos\Phi \cos\Psi) + Z(\cos\Phi \sin\Theta \sin\Psi - \sin\Phi \cos\Psi)$$

$$Z' = -X(\sin\Theta) + Y(\sin\Phi \cos\Theta) + Z(\cos\Phi \cos\Theta)$$

The linear vector equations can be reduced for the special case of angular rates, as shown below.

Angular Rate Transforms

Earth rate to Body rate:

X_R, Y_R, Z_R are the body rotation rates about the X, Y, Z axes: [2]

$$X_R = \dot{\Phi} - \dot{\Psi} \text{SIN } \Phi$$

$$Y_R = \dot{\Theta} \text{COS}\Phi + \dot{\Psi} \text{COS}\Theta \text{ SIN } \Phi$$

$$Z_R = \dot{\Psi} \text{COS}\Theta \text{ COS}\Phi - \dot{\Theta} \text{SIN } \Phi$$

The angular rate equations can be inverted and solved for the Earth angles. The resulting Earth angle angular rates can be integrated to solve for Earth angles, as shown below. [2]

Body Rate to Earth Angle Transforms

$$\Theta = \int (Y_R \text{ COS}\Phi - Z_R \text{ SIN}\Phi) \, dt$$

$$\Phi = \int (X_R + (Y_R \text{ SIN}\Phi + Z_R \text{ COS}\Phi) \text{ TAN}\Theta) \, dt$$

$$\Psi = \int (Y_R \text{ SIN}\Phi + Z_R \text{ COS}\Phi) \text{SEC}\Theta \, dt$$

These equations have singularities from the tangent and secant functions at elevation angles of +90° and -90°. This can be overcome by adding an additional dimension to the equations (effectively adding another gimbal to the theoretical system.

THE CLOSED LOOP

Using an integration system that corrects biases in angular rate sensors requires a second order loop as shown in Figure 6. The second order loop will apply corrections to an integrator which holds an estimate of the bias adjustment needed for a closed-loop convergence to a reference value for angular output.

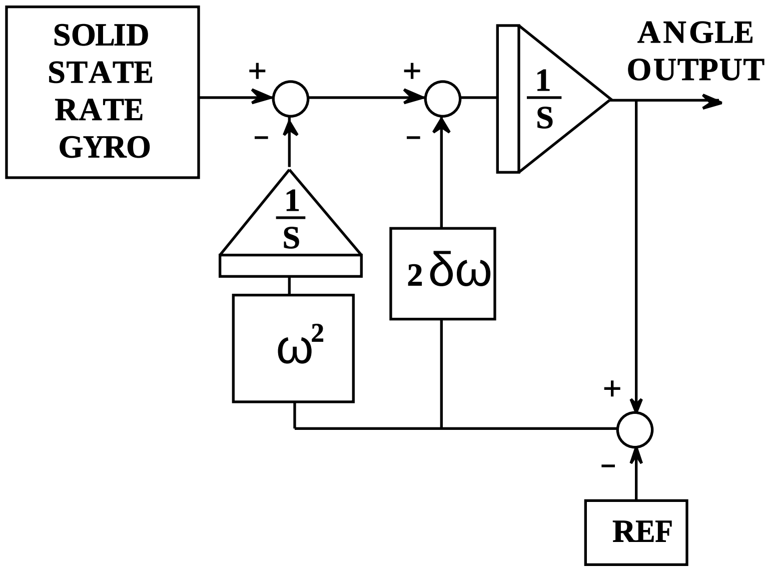


Figure 6. Second Order Control Loop.

Figure 7 shows how this response is arranged in frequency. This figure is very similar to the torquer closed loop figure previously shown as Figure 3. The difference is that the slopes of the roll off between the reference and the gyro crossover point are steeper, as this is a second order system. The result then is that the gyro performance transitions to the reference performance much more quickly as frequency is reduced.

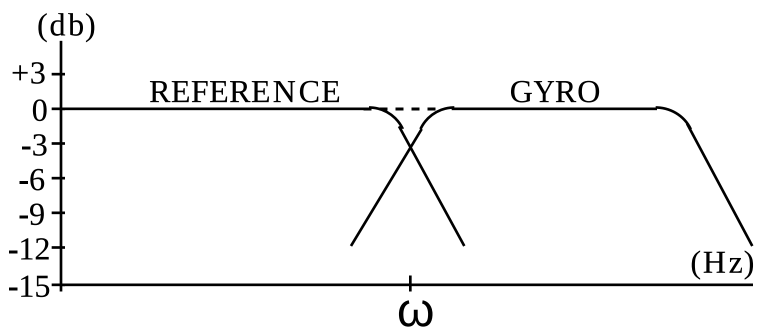


Figure 7. Second Order System Spectrum.

Three (3) angular rates sensors are required in order to fulfill the requirements of maintaining accurate vertical tracking in all attitudes. Since the sensors need bias correction, and therefore closed loop correction, there needs to be a reference for all axes. Two pendulums are used for vertical references and a fluxgate magnetometer is needed for a heading reference.

One of the problems with the second order system shown in Figure 6, is that the bias estimate for each axis of sensor is characteristic for that sensor alone and, therefore, this bias integrator must exist in a body axis format. The division between body axis and earth axis portions of the system, shown in Figure 8 as a dotted line, represents a transform set. In that first case, the body axis angular rates are converted by a transform to earth axis rates that are then integrated to earth angles. In the second case, a transform takes the earth axis errors and converts them to body axis errors for integration as bias correction signals.

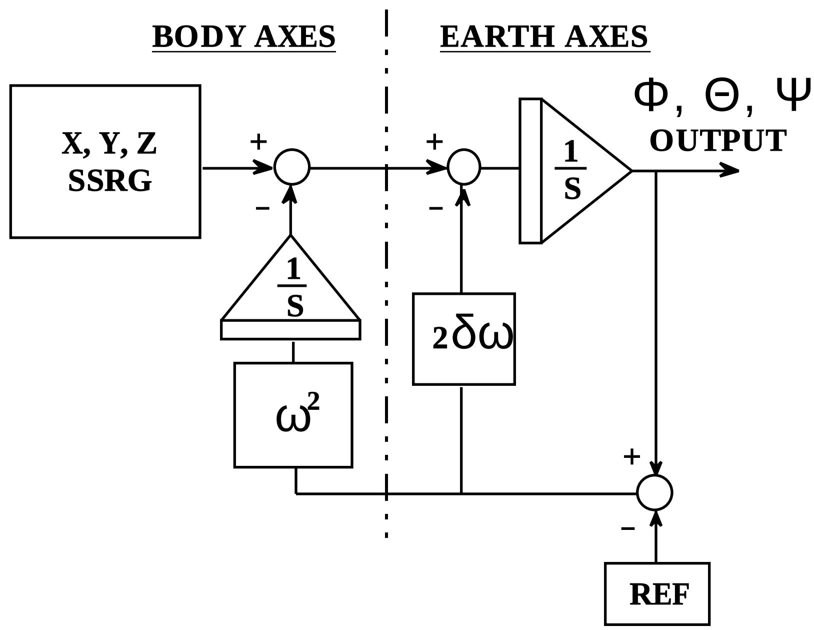


Figure 8. System Reference Axis Distribution.

This system has more flexibility than a mechanical gyro system. One example is that errors can be detected and treated non- linearly so that larger transients can be clipped from the system.

SENSORS

An important part of building such a system is the selection of appropriate sensors. Mechanical gyros, costing thousands of dollars per axis, have hysteresis on the order of .05°/second which would mean that in 20 seconds, one degree of error could exist. Vibrating element solid state angular rate sensors, on the other hand, have no detectable hysteresis. Such sensors are currently available from several sources and all are known for reliability resulting from no moving parts, quick start-up, and low cost since the sensors tend to be more electronic than mechanical. [3]

The preferred angular rate sensor is the Vibrating Structure Gyro (VSG) made by British Aerospace Systems & Equipment Ltd. and is a resonant cup configuration. The rim of the cup vibrates as shown in Figure 10. This is a device that uses Coriolis effects to sense angular rates around one axis.

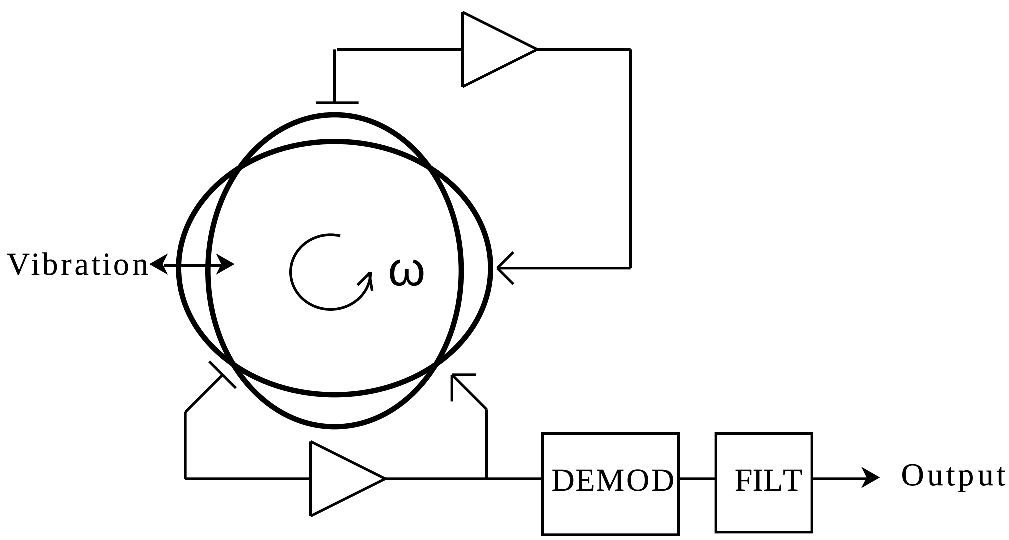


Figure 10. Solid State Rate Gyro.

Typical performance specifications are as follows:

Environment	Specification
Temperature	
Operating	-40 to +85°C*
Storage	-55 to +110°C
Bias	±5°/second over the temp range
Scale Factor Temperature Coefficient	<±0.05 %/°C
Maximum Range	>1000°/second
Linearity Error	<0.3%
Hysteresis	Negligible
Bandwidth	>80 Hz
Vibration (operating)	<0.05 G2/Hz (20 Hz to 1.5 KHz)
Vibration (survival)	<0.1 G2/Hz (20 Hz to 1.5 KHz)
Shock	1000 G 3 ms 1/2 Sine (all axes)

*note: extendible to -55°C without harm, but with some reasonable growth in bias & scale errors.

The merits of this product are ruggedness, high reliability (~50,000 hours MTBF), low cost, quick start up, low weight and small size.

Watson Industries has found that relative resolution of solid state rate gyros such as this are far below Earth rate when the bias of the rate sensor is under control. [4]

Another part of this system that needs to be selected is the vertical reference. In this case, a liquid pendulum that uses capacitive sensing has been selected . The reasons for this choice are the lack of moving parts (no wear and no hysteresis) and the capacitive isolation of the fluid, which tends to keep the fluid from being damaged through electrolysis.

Also selected is a fluxgate magnetometer that is triaxial to avoid the mechanical parts and attitude limits of a gimbal system. It was decided to use the pendulum to make a synthetic gimbal for the fluxgate data.

SYSTEM CONFIGURATION

As was shown before, error correction will drive the frequency response system, especially the crossover between the reference and the gyro, in controlling the output signal. Earth rate is not the major concern since, in this case, a much faster time constant is being set up than would have been for a spinning wheel gyro.

The time constraints are related to the noise of the references versus the noise of the rate sensor. Vibrating element rate gyros tend to have broad band noise, the amplitude of the noise depending on the type and size of the sensor. A time constant in the range of 60 to 120 seconds is used for the RG600P because of its high stability and low sensitivity to vibration.

The hardware used to implement this system is shown in Figure 11. The limits on performance of the device are the resolution of the analog to digital converter, the speed of the microprocessor for iterative integrations and the precision of the digital to analog converter which produces data outputs.

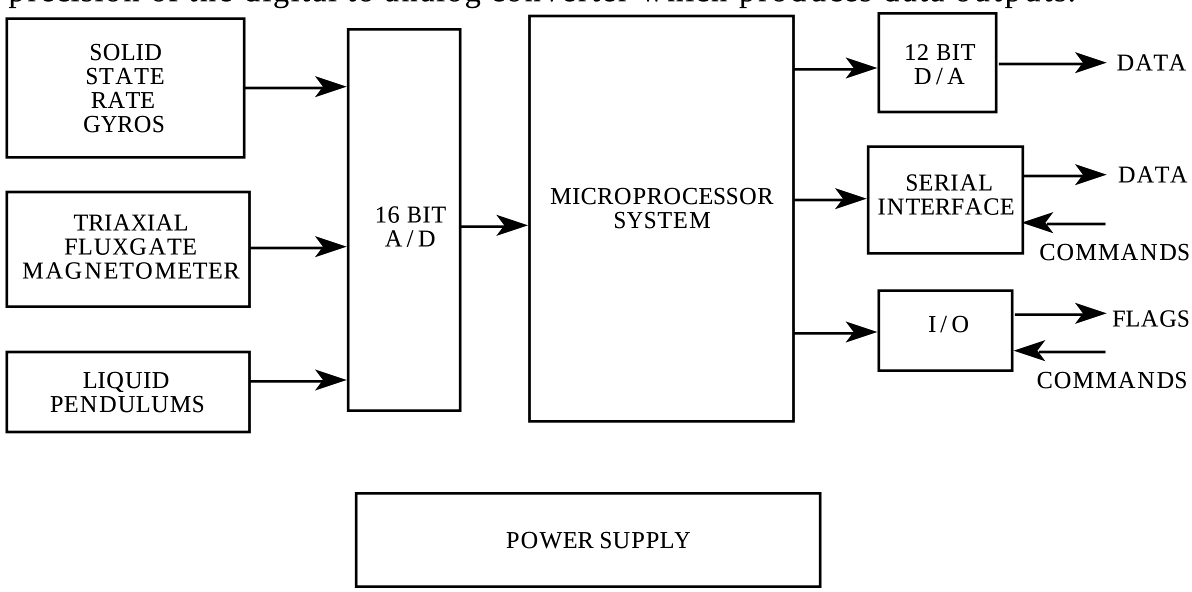


Figure 11. Attitude System Hardware.

The microprocessor hardware includes an EEPROM memory block which is used to enhance the system accuracy and performance in many ways. All of the system inputs are bias corrected, gain corrected, axis alignment corrected, etc. using data entered in this EEPROM block. The EEPROM block also contains limit values, output format flags and time constants for the system. All of these factors can be input or modified by the user from an external terminal thus allowing intricate adjustment of the whole system while keeping the system sealed.

Such a software-based system allows variations in the loop such as alternate routines for initialization, variable time constants that are set by logic conditions, the ability to coast in inertial mode when the references are in an over-range condition. The main functions are the ability to analyze the signature of the error signals and to set limits and time constants accordingly.

The main advantage of such a system is the low cost. The cost advantage is available in two ways. First, savings come from the fact that this system also supplies the heading gyro functions. Second, savings come from life cycle costs since the MTBF of such a system is in the order of 50,000 hours vs. the 200-2000 hours that are typical in spinning wheel gyro systems. This is a direct result of the reliability of non-moving part systems and, therefore, the reliability is a technical advantage.

Other technical advantages are the quick initialization of the system, the benign nature of the system to dynamic motions and the elimination of the gimbal lock problem.

The results are the specifications listed below:

SPECIFICATIONS

1) Output range and scale factor

- Pitch Rate ±100°/s (10°/s/V) (Positive for Nose Up)
- Roll Rate ±100°/s (10°/s/V) (Positive for Roll to Right)
- Yaw Rate ±100°/s (10°/s/V) (Positive for Right Turn)
- Heading Rate ±100°/s (10°/s/V) (Positive for Right Turn)
- Bank ±180° (18°/V) (Positive for Bank to Right)
- Elevation ±90° (18°/V) (Positive for Nose Up)
- South Heading 0-360° (18°/V)
  (North= ±10V; East= -5V; South= 0V; West= +5V)
- North Heading 0-360° (18°/V)
  (South= ±10V; West= -5V;North= 0V; East= +5V)

2) Rate Accuracy Static <±0.1°/sec; Dynamic <±2%

3) Attitude Accuracy Static <±1°; Dynamic <±2%

4) Heading Accuracy Static <±2°; Dynamic <±2%

5) Weight less than 48 Ounces

6) Power Less than 1/2 Amp at 28 Volts DC

7) Error correction time constant is about 90 seconds
(error correction is reduced or switched off during extreme maneuvers)

9) Error growth when error correction is switched off will be about 0.3°/minute

10) No attitude limits

The above system includes a user configurable serial interface. The user may select any from among attitude, rate and reference data channels, baud rates of from 1200 to 9600 baud, formats (ASCII decimal and binary), and asynchronous or synchronous transmission. The configurations made can be set as either temporary or as power up default values.

IMPLEMENTATION

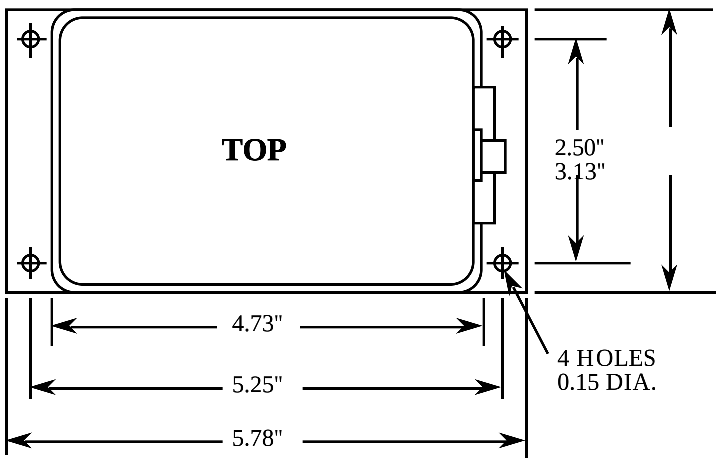
There are three ways to use this AHRS on a vehicle. First, it can be used for instrumentation. The bandwidth of the system, the versatile serial interface and the complete sensor set make it an excellent resource for flight test data. Second, it can be used for stabilization. The angular rate sensor analog outputs can be added to the command signals to easily form a closed velocity command loop. The 80 Hz bandwidth and the body axis format makes this suitable. Finally, adding rates and attitude signals together with attitude commands gives a simple control system.

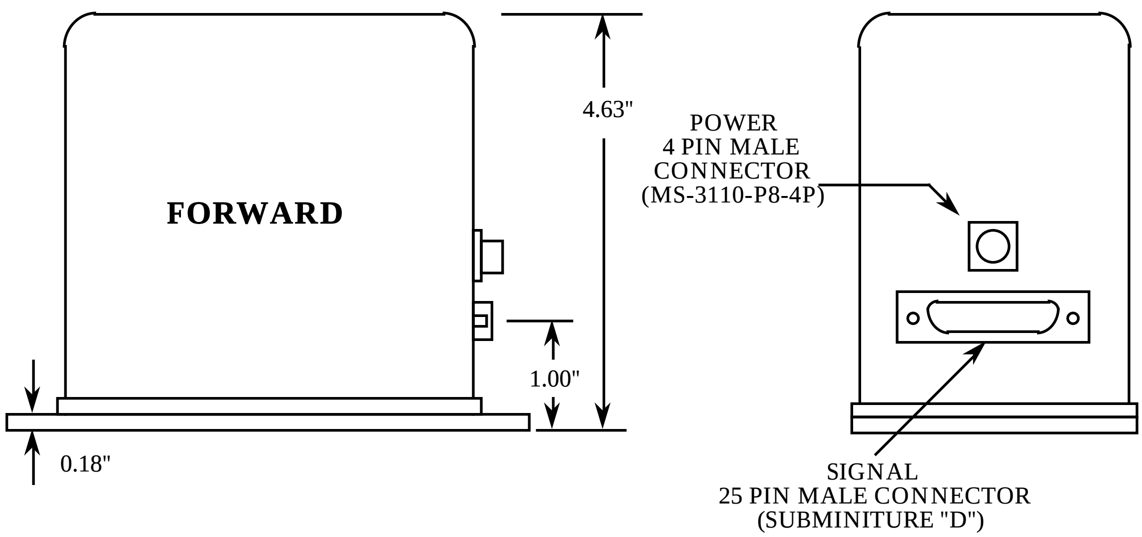
POWER PINOUT

PIN	FUNCTION
A	
B	+12 VOLTS DC
C	
D	POWER GND.

SIGNAL PINOUT

PIN	FUNCTION
1	
2	RS-232 INPUT
3	RS-232 OUTPUT
4	
5	
6	
7	SIGNAL GROUND
8	USER CHANNEL 1 INPUT
9	USER CHANNEL 2 INPUT
10	VELOCITY ERROR FLAG
11	SOUTH HEADING FLAG
12	INVALID VELOCITY COMMAND
13	REFERENCE OUTPUT COMMAND
14	HEADING NORTH
15	HEADING SOUTH
16	BANK
17	ELEVATION
18	FORWARD VELOCITY INPUT
19	USER CHANNEL 3 INPUT
20	HEADING RATE
21	ROLL RATE
22	USER CHANNEL 4 INPUT
23	PITCH RATE
24	YAW RATE
25	COAST MODE COMMAND





AHRS-E303 PHYSICAL CONFIGURATION

PERFORMANCE

Although the AHRS concept has been operational for several years, some very definitive tests of the sensor system have only recently been made. The results of one such test (using a less qualified solid state rate gyro in an AHRS-C303) are shown in Figure 12. In this test, the AHRS was commanded to an open loop condition so that the output was related strictly to the drift of the angular rate sensor from an initial condition. Admittedly, this is not a typical performance curve for the system, but one which showed the best available performance from the sensors. In actual practice, the system under test used a 12-bit digital to analog converter to correct biases which calculates out to the ability to correct angular rates to a level of 1.4°/minute. Since system time constants of 15 to 30 seconds are used, the usual angle drift of the unit would be about 0.35° to 0.7° in a normal closed loop mode.

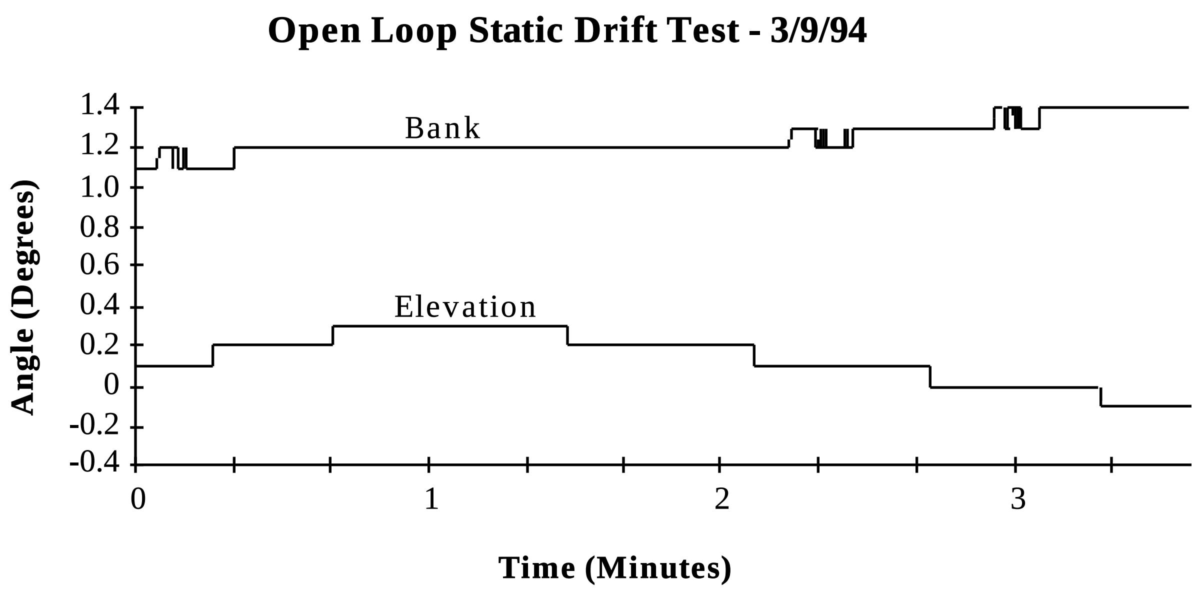


Figure 12. AHRS-E303 Static Open Loop Drift.

The proposed system, however, would have 16 bit bias correction, less than one half the bias to correct and a closed loop time constant of about 1.5 minutes. The drift of the system in open loop mode would be reduced to approximately 0.3°/minute, neglecting earth rate and 0.3° in the closed loop mode.

In recent years, these systems have been in practical use on a wide variety of platforms. They have demonstrated capability to adapt to projects as diverse as undersea vehicles and supersonic jet aircraft.

The first example is that of a remote operated helicopter manufactured by a company in France. The helicopter is a small vehicle using an engine in the approximate range of 5 HP. Its use is for video surveillance and, as such, needs stabilization for the frame of the vehicle in order to generate the highest resolution for the picture. The AHRS sensor system has demonstrated the ability to hold absolute accuracy in attitude of approximately 1 degree and to perform its stabilization functions under extreme vibration environments.

Another example comes from an instrumentation project operated by Johns Hopkins University in Laurel, Maryland. The AHRS is installed in a wing pod that has been carried by various jet aircraft air frames, including an A-4 and a F-16.

CONCLUSIONS

It has been shown that a strap down solution can be used to replace the traditional spinning wheel gyroscope with improved performance. The system, because it is software-based, can be successfully optimized for a wide variety of platforms.

REFERENCES

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[3] William S. Watson, Vibrating Element Angular Rate Sensor for Precision Applications, IEEE Position Location and Navigation Symposium, No. 90CH2811-8, pp. 17-20, March 1990.

[4] William S. Watson, Improved North Seeking Gyro, IEEE Position Location and Navigation Symposium, No. 0-7803-0468-3/92, pp. 121-125, March 1992.