GyroWheel™ - An Innovative New Actuator/Sensor for 3-axis Spacecraft Attitude Control

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Abstract

The Bristol GyroWheel is an innovative attitude control system device that provides both an angular momentum bias and control torques about three axes while at the same time measuring the spacecraft angular rates about two axes. The principles of operation of this device are explained and the flight model design is described that is targeted at small satellite applications which is currently under development. A fully functional prototype of the GyroWheel has been developed that has demonstrated the actuator and rate sensing capabilities and some of the test results are given. One of the key advantages of the GyroWheel is that, for earth pointing applications, it can be used with a single 2-axis earth sensor to provide fine pointing control in all three axes. This allows for reducing the mass, power above all cost of this class of ACS system. A GyroWheel based ACS design is developed for an example case consisting of a small earth pointing microsat mission. Performance simulations are given that show that the pointing control can be maintained within 0.1 degrees in all axes. The GyroWheel promises to fulfill the need for low cost, low mass, high reliability and high accuracy attitude control systems for applications such as communications, remote sensing, and space science.

Introduction

With the rapidly expanding commercial space market, there is a growing need to dramatically reduce the spacecraft cost while maintaining high reliability and aggressive performance capabilities. Traditionally, one of the more expensive elements of a spacecraft is its Attitude Control System (ACS) due to the high cost of the hardware and the extensive integration and testing that is required. Hence, simplifying and reducing the cost of the ACS subsystem while maintaining the fine pointing performance requirements can go a long way to significantly reducing the cost of the spacecraft. The majority of the commercial space market is primarily in the communications and the remote sensing applications. This class of missions are characterized by requiring earth pointing ACS systems that maintain relatively fine pointing accuracies.

The GyroWheel is a new device that is being developed by Bristol Aerospace Limited that provides angular momentum bias to the spacecraft and is capable of imparting control torques about all three axes while also measuring the spacecraft angular rates about two axes. Hence, this device is both an actuator and a sensor at the same time. The multi-function capability of the GyroWheel allows for implementing an ACS design with a significant reduction in the number of ACS components that are required to achieve the same level of fine pointing performance. In particular, the GyroWheel can be combined with a high accuracy 2-axis earth sensor to provide a full fine pointing 3-axis attitude determination and control capability (i.e., a direct yaw sensor is not required). This implementation approach results in a significant decrease in the size, mass, power and ultimately costs for the spacecraft ACS subsystem.

This paper starts with a brief description of current spacecraft attitude control techniques highlighting the fact that most spacecraft ACS systems generally use direct control of angular momentum to effect the pointing control, and many spacecraft in fact typically use gyros to augment the earth sensors to provide yaw knowledge. The GyroWheel is then described and the principle of its operation is explained. The development status of the system is outlined and the working prototype of the device is described and some preliminary test results are given. Finally to demonstrate the application of the GyroWheel for an earth pointing spacecraft mission, an ACS design is described that uses the GyroWheel and a 2-axis earth sensor and computer simulation results are given that show the ACS performance for a small spacecraft in a low earth orbit.

Spacecraft Attitude Control Techniques

Spacecraft attitude control systems are generally based on the direct control of angular momentum. The ultimate goal is to point a satellite or portions of a satellite at the Earth, another spacecraft or at other celestial bodies. Experience has shown that the most reliable method for achieving control is to maintain a non-zero angular momentum state that can be achieved by including spinning rotors within the spacecraft to provide control about all three axes. Though virtually all three axis spacecraft include spinning rotors, the control system and use of the rotors does depend on the ultimate mission, whether it is a geosynchronous (GEO) mission or a low earth orbit (LEO) mission. Each of these missions include different modes of operation, all of which may be affected by direct control of the angular momentum.

GEO spacecraft, primarily used for communications purposes, are maintained in a near circular orbit above the equator at an altitude such that the orbit period is 24 hours and the satellite nominally remains fixed in position with respect to a point on the Earth's equator. The orbit is not free from perturbations and thruster forces must be applied periodically to maintain station. These station keeping manoeuvres either correct for orbit inclination disturbances, which effect North and South motions of the satellite, or for East and West accelerations. An additional mode of operation for GEO spacecraft is the transfer orbit from LEO to GEO. A highly elliptical transfer orbit is used to get the spacecraft from earth to injection into the final GEO orbit, using thrust from an apogee engine.

LEO spacecraft used for communications and remote sensing often have 14-15 orbits per day, and they also require periodic orbit or station keeping manoeuvres to maintain the required orbital parameters. These orbits are often highly inclined to the equator where the asymmetric gravitational field of the earth causes the orbit plane to precess. Also at these low altitudes the aerodynamic forces are not negligible and cause the orbital altitude to decay. Additionally, for LEO communications applications, spacecraft constellations are generally used where information is transmitted between spacecraft and also to distributed ground stations. Hence, the placement of all spacecraft in the constellation must be accurately known. LEO spacecraft are typically injected directly into their operational orbit and therefore do not have an orbit transfer mode of operation as do the GEO spacecraft.

Most of the life of a spacecraft (LEO or GEO) is spent quietly pointing at the earth or other target, with the control system absorbing external disturbances to maintain pointing. The major source of external disturbance for GEO satellites is due to solar radiation pressure which creates a disturbing torque, while for LEO spacecraft the primary disturbance torques are caused by the Earth's gravitational and magnetic field, and to the aerodynamic forces. Because these disturbances are very small, it is possible to provide full three axes of control while actually measuring attitude pointing errors in only two axes by using an earth sensor. The rotations about the yaw axis, which joins the spacecraft with the Earth's centre, are difficult to measure on a continuous basis. However, by adding a rotor to the spacecraft directed along the orbit normal direction which is orthogonal to the yaw axis (the pitch axis), the yaw rotation error can be constrained to remain within an acceptable envelope through a form of gyrocompassing provided that the angular momentum is sufficiently large. The rotor size and angular momentum is determined by the allowed yaw errors and the disturbance torque through the well known relation:

$$y = \frac{T}{w_o H}$$

with y the yaw attitude error, T the disturbance torque, w_o the orbit angular velocity and H the rotor angular momentum.

The yaw attitude control accuracy can be improved, and/or the required rotor angular momentum can be reduced if spacecraft angular velocity measurements can also be used to generate the control actuation in addition to the attitude pointing errors about two axes obtained from an Earth sensor, or other sensor source. Direct attitude control of the spacecraft about all three axes (i.e., roll, pitch and yaw) is accomplished by managing the internal angular momentum state. Thus, for example, by torqueing between the spacecraft body and a pitch rotor, the rotor can be made to change speed in one direction and the spacecraft will change speed in the opposite direction. Similar control actuation can be obtained by simply tilting the spinning rotor in the direction of the desired torque. The increase in angular momentum along the desired axis due to the component of the rotor angular momentum along this axis is equivalent to applying a control torque.

When the station keeping manoeuvres occur (often on a two week operational cycle for GEO spacecraft), the thruster activities result in disturbance torques which are orders of magnitude larger than during normal operation. Thus, the yaw pointing error can no longer be constrained with the normal rotor angular momentum. As a result it is necessary to measure changes in the yaw pointing error and actively provide control. For GEO spacecraft, for example, it is common to use a yaw gyroscope for the duration of the manoeuvre to measure the yaw errors. Control is usually exercised through modulation of the thrusters which are used for the station keeping operation, or through special purpose attitude control thrusters.

The transfer orbit phase for a GEO spacecraft is often accomplished with the spacecraft rotating slowly at roughly 5 revolutions per minute. During the thrusting phases, and depending on the spacecraft inertial properties, a nutation or wobbling type of motion may develop unless direct control is exercised. This direct control may be accomplished by applying appropriate torques to the internal rotors in the spacecraft under the direction of signals generated from gyroscopes, accelerometers or by other means. It is also possible to remove the effects of an unbalanced spacecraft by applying appropriate torques to the internal rotors.

It is also necessary that any attitude control system address failures as an intimate part of the design process. One of the reasons that a non-zero momentum state is preferred for ACS systems is that the failure mode associated with loss of spacecraft attitude control is well known. For example, angular momentum is conserved, so that even if speed control of the internal rotors should fail for any reason, momentum will be transferred to the spacecraft body. In this case the spin axis direction is known and spacecraft health can be maintained even though operation of the spacecraft payload may be interrupted. Ideally, in the event of a failure, the system and its components are capable of reconfiguration to redundant units so that no operational outage occurs.

There are only a limited number of ways that high accuracy three axis attitude control is currently obtained. All are based in some way on control of stored angular momentum. For high accuracy, it is possible to use three or more reaction wheels, so that the total angular momentum magnitude and direction can be controlled, within the spacecraft body, by varying the speeds of each of the wheels. The wheels are usually mounted in an orthogonal triad. To provide redundancy (commonly done for GEO satellites), four wheels can be used mounted in a skewed configuration so that any three wheels can be used for control in the event of the failure of any one wheel. A major drawback of the multi-wheel configurations is their mass, power requirements and cost as they require a number of wheels, with attendant redundancy, and the associated duplicated electronic boxes.

An alternative method of momentum control that is used by commercial spacecraft suppliers uses a double gimballed momentum wheel in which a single momentum wheel is mounted within a two axis gimbal system. Actuation of the gimbals provides control of the angular momentum within the spacecraft body as required for control while limiting the total number of rotors to just a prime and possibly a redundant system. A conventional double gimballed wheel consists of a momentum wheel mounted on an articulating platform. A trio of stepper motor driven linear jack screws is used to provide the tilt capability. The three actuators are needed to provide some redundancy since jack screws can wear and eventually fail. A total angular deviation of about 6 degrees is adequate for earth pointing configurations. In principal, for earth pointing applications, the double gimballed wheel has all the advantages of three reaction wheels with a momentum control capability in all directions while using but a single wheel. It suffers from two major disadvantages. The first is a result of the actuators which operate in discrete steps. This limits the pointing accuracy and requires careful nutation control. The second disadvantage is the complex mechanical configuration as it has numerous points of possible failure. These mechanisms add mass, cost and unreliability which are not desirable for commercial satellites that tend to be highly cost sensitive.

GyroWheel Description

The GyroWheel is a form of double gimballed momentum wheel based on spinning gimbals as opposed to the usual non-spinning gimbals that have been used. This innovation provides not only a capability to control the angular momentum in three axes but to provide two axes of angular velocity measurement at the same time. The device, shown in Figures 1 and 2, uses a spinning rotor (or wheel) that is attached to a drive shaft through a novel “spinning flex-gimbal” suspension system that allows for actively tilting the rotor up to 7° while it is spinning to provide a “momentum steering” capability. Due to the unique nature

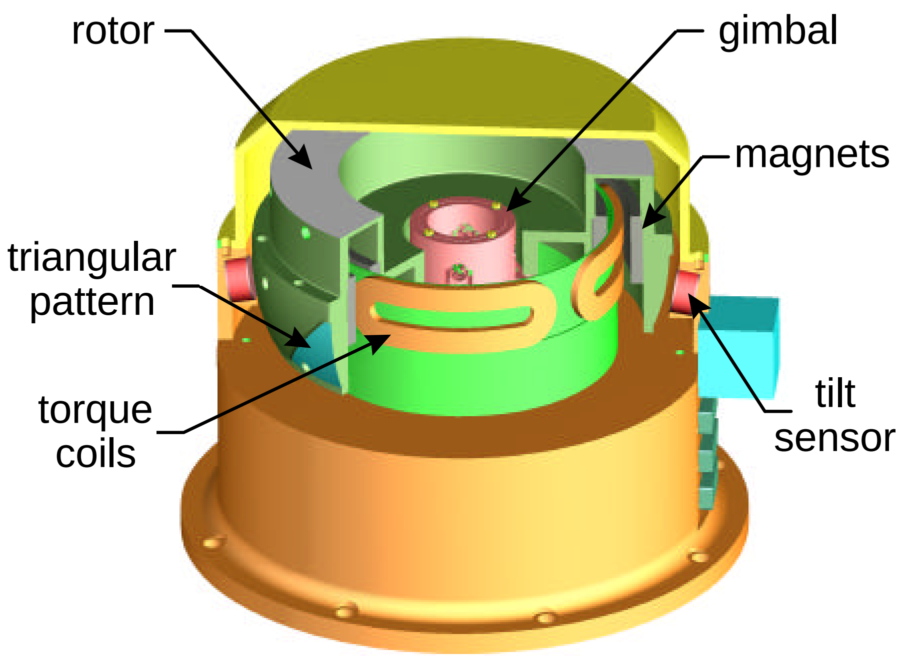

Figure 1 Cut-away view of the smallsat version of the GyroWheel - model GW-440

of the gimballed rotor suspension system, the device can also function as an inertial grade two-axis gyro..

Torque coils that are fixed to the housing, are used to interact with permanent magnets mounted in the rotor to allow steering the rotor spin axis (i.e., the rotor angular momentum vector). Two pairs of small inductive pick-offs are used to provide a tilt measurement by sensing the current pulses that occur at the edge transitions of a triangular pattern machined on the outside spherical surface of the rotor (shown in Figure 1). The timing between consecutive edge transitions can then be calibrated to provide a precise tilt angle measurement.

The GyroWheel gimbal is shown below in Figure 3. Integral cross-flexure pivots are used on two orthogonal axes to enable tilting the spinning rotor up to 7° from the drive shaft. Use of the flex-pivots at the two hinge points allows for ensuring infinite life of the gimbal as the operating stresses are designed to be considerably lower then the so-called "fatigue limit" of the very high strength steel used for the gimbal so that they will not wear out or experience fatigue. Additionally, the flex pivots in the gimbal allow for "tuning" the system. When the rotor is tilted and is spinning, the gimbal ring, which is the piece that connects one set of hinge points with the other orthogonal set of hinge points, tends to flutter at twice the spin frequency (exactly like the cross piece in a conventional U-joint). At a particular spin speed, the inertial forces due to the fluttering gimbal ring tend to cancel the spring forces of the flexure (to a first order approximation) so that the rotor behaves very nearly like a freely spinning rotor in space allowing the device to function as a very precise two axis gyro. This is the same basic concept behind the classical Tuned Rotor Gyroscope (TRG), that has been used for many years in space, and has demonstrated extremely high rate sensing accuracies are achievable (e.g., in the order of 0.01 deg/hr has been demonstrated). The innovation with

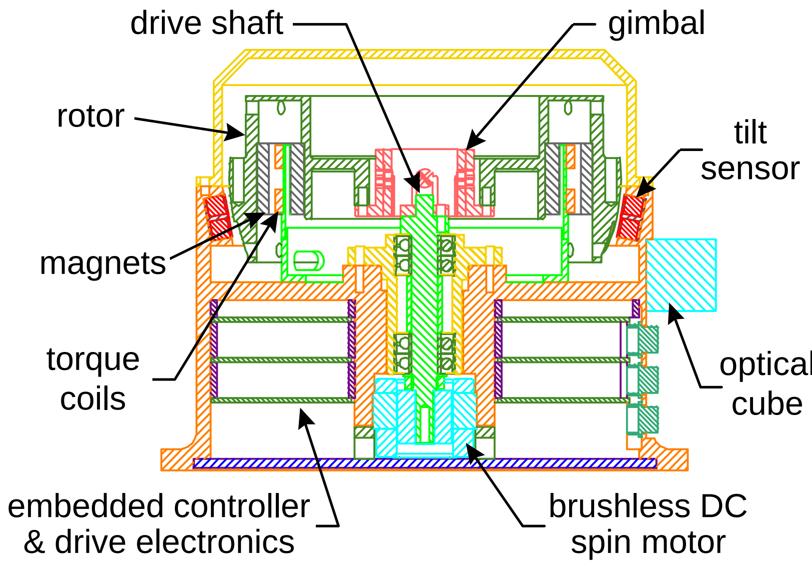

Figure 2 Cross-sectional view of the GyroWheel™ - model GW-440

the GyroWheel is the ability to extend this basic principle to a device which can also be used as a 3-axis actuator. This however introduces some unique design challenges and leads to some fundamental differences from the TRG. One is that the device is never really tuned (as it is for a TRG) as its spin speed is constantly changing within +- 20% of the tuned speed and it must operate at relatively large tilt angles of up to 7 deg (a TRG only operates at a zero tilt). These are rather substantial departures from the classical TRG and much of the innovation is in the design of the GyroWheel gimbal and in the signal processing algorithms and the calibration approach. The gimbal design allows for large tilt angles, a range of tuned speeds over the full speed range that can be set at the factory (or bias speeds for the wheel) and can handle the large launch loads. The proprietary signal processing algorithms and calibration technique address the issue that when the rotor is not tuned and is tilted, torques are required on the rotor to maintain its orientation relative to the case, and these must be known very precisely.

A digital control system is used to maintain the rotor orientation (i.e., tilt angles) and the rotor speed at the desired values commanded by the spacecraft attitude control system. When the rotor is maintained at a constant tilt angle and spin rate, it requires a specific amount of current in the torque coils. This can be determined for all tilt angles and spin speeds within the operational range through detailed calibration. As the spacecraft experiences an external rate, the current needed in the torque coils to hold the rotor at a given orientation and speed increases. Hence, it is this difference between the calibrated current needed to hold the rotor at a given orientation and speed and the actual measured current in the coils that is used to establish the spacecraft external rates about the two axes perpendicular to the drive shaft.

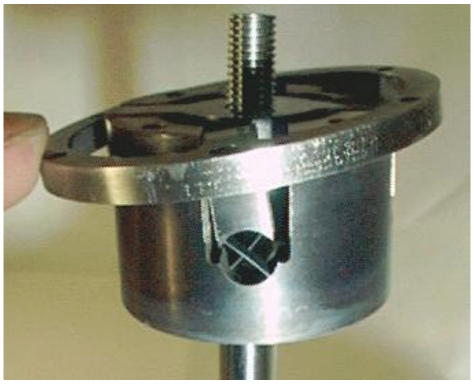

Figure 3 GyroWheel™ Gimbal

The GyroWheel digital controller design is based largely on Bristol's radiation hardened and high reliability spacecraft Command and Data Handling system (C&DH) that is currently being development for flight onboard the Canadian Space Agency's SCISAT small scientific satellite mission expected to fly in early 2002. To maintain high reliability, the controller uses rad-hard components, in particular, a Harris RTX-2010 16 bit micro-processor, rad-hard RAM memory, and Actel FPGA's. Three boards are housed internally in the GyroWheel: a processor board that performs the tilt control; a motor driver board; and an I/O board.

The performance characteristics of the model GW-440 design are outlined in Table 1. The mass and power estimates are based on the demonstrated performance of a fully functional prototype that has been developed (discussed in the next section). The rate measurement accuracy is a target specification that is expected to be achieved but has not yet been demonstrated (testing is currently underway).

The GyroWheel design is scaleable for a variety of momentum ranges. Model GW-440 shown in Figures 1 and 2 is a smallsat version that has an angular momentum range of 1 to 4 N-m-s. This is the unit that is presently being developed and is targeted to be flight qualified in early 2002. Additionally, a large version of the GyroWheel is planned that would be suitable for large LEO spacecraft and GEO communications satellites with a momentum range of approximately 20-80 N-m-s. The design would be very similar to the model GW-440 but the rotor would have a larger diameter of approximately 37 cm and the gimbal design would be modified to handle the larger loads that result from a more massive rotor.

Table 1 GyroWheel™ Flight Model GW-440 Performance Characteristics

Size (cm)	19 dia. x 15 high
Mass (kg)	5.5
Steady State Power (W)	< 8 (at 1 Nms bias)
Bias Momentum Range (Nms)	1-4
Speed Range (rpm)	1200 – 6000 rpm
Momentum steering capability	±7 deg in each axis
Max. control torque (mNm) (about each axis)	> 40
Static balance (gram-cm)	< 0.1
Dynamic balance (gram-cm^2)	< 3
Alignment	calibrated to integral alignment cube
Rate measurement bias error (deg/hr)	0.1
Electrical Interface	Serial RS-422 28 V DC unregulated

Prototype Test Results

A fully functional prototype has been developed, shown below in Figure 4, that has demonstrated the actuator and rate sensing features of this device.

The prototype is functionally equivalent to the model GW-440 design in all important areas to allow for meaningful design validation tests. The primary differences from the flight model design are that it is somewhat larger diameter to allow for some working space and adjustability for the tilt sensors (i.e., a separate tilt sensor mounting ring is used), analog drive electronics are used, and the electronics boards are housed in an external electronics box to the GyroWheel housing to allow for easier access for modifications and trouble shooting.

One of the key issues that was demonstrated with the prototype is the ability for the gimbal flexures to withstand the launch loads by using integral deflection limit stops. Load tests have been performed that have shown that the gimbal flexures can handle loads greater than 30 g's. Hence, the gimbal design with its built-in stops allows launching and handling the GyroWheel without the need for a caging system for the rotor. This solution is very cost effective, reliable and practical to implement.

The testing also confirmed that the power required to provide the control torques about the two tilt axes is extremely low (fractions of a watt), confirming that most of the power requirements of this device is due to the motor and drive electronics which is not unlike conventional single axis momentum wheels. The average power of the prototype running at 1500 rpm, which corresponds to a bias angular momentum of 1 Nms, was measured to be 5.7 W (4.5 W for the GyroWheel, most of which is for the spin motor, and 1.2 W for the drive electronics). Additionally, the testing has demonstrated that very large peak torques can be obtained about the tilt axes if desired with only a very minor impact on the overall peak power requirements. This may be an advantage for some missions.

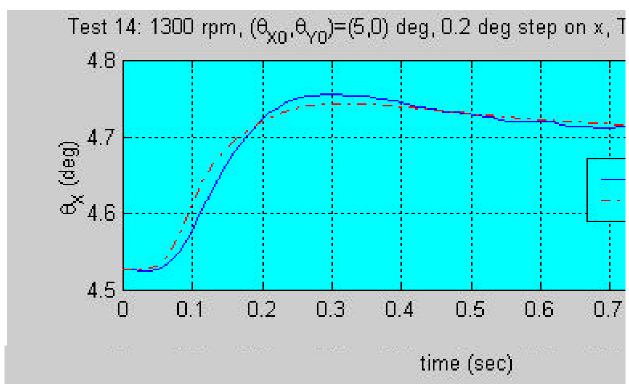

Figure 5 Rotor Tilt angle step Input Test Results

Figure 4 Photograph of the GyroWheel™ Engineering Model

Tilt control system tests were also performed that compared the tilt control system performance with analysis results. These tests consisted of imparting various tilt angle step inputs from a variety of initial tilt angles and rotor speeds and measuring the rotor tilt response. The results from a typical test is given Figure 5 that shows that the rotor tilt control system performs very much as expected.

Also, due to the gimballed rotor implementation, it is possible to balance the rotor very accurately resulting in very low vibration disturbances to the spacecraft. Balance screws are added to the rotor on 3 radial balancing planes and one axial balancing plane. The static balancing is performed by placing the GyroWheel on a tilt table facility developed at Bristol that has an autocollimating telescope mounted directly on the table. This facility can determine when the tilt angle is zero by viewing a polished surface on top of the rotor with the telescope. The device can then be statically balanced by measuring the current needed in the torque coils to bring the rotor tilt angle to zero. This is done with the device tilted so that the gravity vector is aligned with the shaft in both positive and negative orientations (note the rotor is not spinning for this test). The dynamic balance is performed by simply running the rotor in an open loop mode (i.e., no tilt control) and measuring the resulting nutation of the rotor and its phasing with the tilt sensors. Software was developed that allows for taking these measurements and determining which of the rotor balance screws need to be turned and by how many rotations. This balancing approach allows for performing the fine balancing of the rotor very accurately and also very expediently. The balancing results obtained for the prototype are as follows

static imbalance: 0.17 gram-cm

dynamic imbalance: 2.5 gram-cm^2

Note that these results can be further improved if desired, particularly if a 6-axis force table is used to improve the static balancing. Also, due to the mechanical suspension of the rotor using the flex-gimbal, any residual dynamic imbalance manifests itself in a small nutation about the spin axis and only extremely small (i.e., negligible) torques are actually transmitted to the spacecraft through the motion of the gimbal flex pivots which have a very low bending stiffness (i.e., 75 mN-m/rad).

Rate sensing tests of the GyroWheel prototype are presently being conducted at the Defence Research Establishment Ottawa (DREO) Navigation Laboratory (NavLab) using a precision multi-axis rate table. The test set-up is shown in Figure 6 where the external drive electronics are placed on a stand above the prototype to allow for placing both the prototype and the electronics in a common thermal enclosure to perform calibration tests over temperature. Preliminary results have shown that the present rate sensing resolution of the device is in the order of a few deg/hour which puts it in the medium rate sensing accuracy class. These results are preliminary at this stage, and detailed multi-position rate sensing calibration tests are presently being conducted that will provide more conclusive rate testing results. However the testing to date has identified the main limitation to this rate sensing resolution as being the inductive tilt sensor that is presently used which requires further design optimized to reduce the noise that it introduces to the torque coil current measurements. An updated tilt sensor is presently being developed that is expected to increase this performance by more than an order of magnitude to allow achieving the 0.1 deg/hour rate sensing accuracy specification that is the design goal. This upgraded tilt sensor head will be incorporated into the prototype and further rate sensing tests conducted.

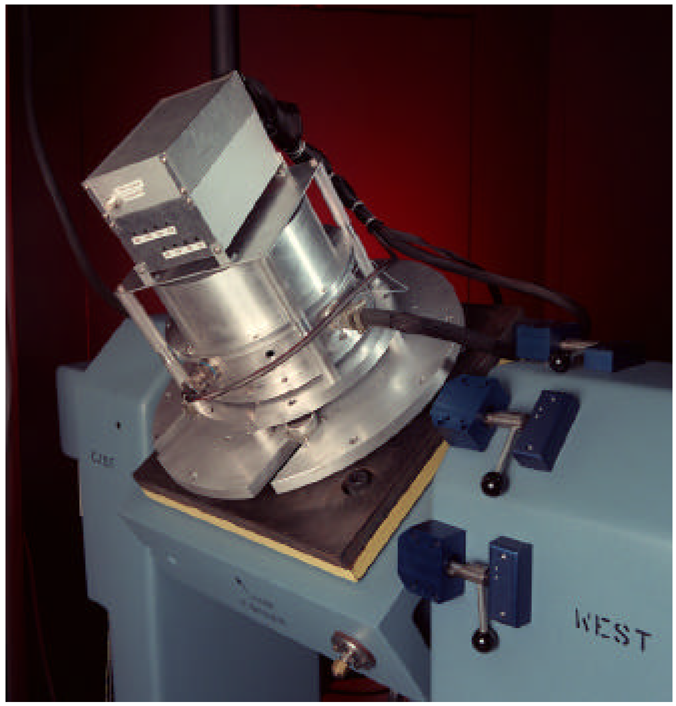

Figure 6 GyroWheel Prototype Rate Sensing Test Set-up on a Precision Rate Table

Attitude Control System Application

One of the benefits of the GyroWheel is that when it is combined with a high accuracy 2-axis earth sensor, it can provide 3-axis fine pointing control for the earth pointing operational mode. To demonstrate this application of the GyroWheel, an ACS design is established for a strawman microsat mission and performance simulations are given.

For an earth pointing application, the GyroWheel would be mounted in the spacecraft so that its spin axis is aligned with the spacecraft pitch axis (i.e., orbit normal). In this configuration, the GyroWheel can control pitch motion by varying the speed of the rotor and can control the roll and yaw spacecraft motions by tilting the rotor about two axes. The GyroWheel would also measure the spacecraft roll and yaw angular rates. The earth sensor measures the roll and pitch angles, and the control accuracy will be ultimately limited by primarily the earth sensor accuracy. The earth sensor cannot directly measure the yaw angle (i.e., rotation about the nadir vector). However, due to the coupling between roll and yaw that exists because of the bias angular momentum from the GyroWheel, a dynamic estimator can be used to compute the yaw angle in real time using the roll angle measurements from the earth sensor and the roll and yaw rate measurements from the GyroWheel.

A possible implementation of the GyroWheel based ACS is shown in Figure 7. In this case, the GyroWheel and earth sensor would be used for the normal earth pointing operations mode, while the magnetometer and magnetic torque rods would perform the other mission specific manoeuvres such as the initial attitude acquisition and momentum dumping. Note that the momentum dumping operations would involve applying torques to the spacecraft by the torque rods that would cause the GyroWheel rotor tilt angle to approach zero and the spin rate to approach the nominal bias speed. This operation can be performed at appropriate times during each orbit and the control system can be configured to ensure that the GyroWheel adequately compensates for this external torque so that it will not adversely affect the spacecraft pointing accuracy.

To demonstrate the pointing performance that is achievable with the GyroWheel based ACS system, computer simulations were performed for an earth pointing microsat configuration. The following spacecraft and orbit features were selected as a baseline:

GyroWheel bias speed:	1500 rpm
GyroWheel bias momentum:	1 N-m-s
Spacecraft mass:	60 kg
Spacecraft size: (solar panels stowed)	$50 \times 50 \times 50$ cm^3
Principal MOI: (2.86,2.86,2.93) kgm^2 (solar panels deployed)	
Orbit:	600 km circular, 98^o inclination

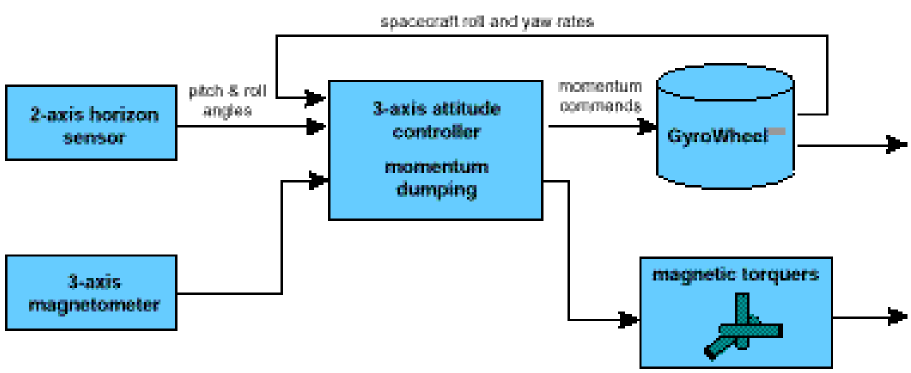

Figure 7 Typical GyroWheel based ACS implementation for earth pointing LEO spacecraft applications

It is also assumed that the earth sensor provides a pointing knowledge of 0.05° (bias = 0.02° and 3s noise = 0.03°) in roll and pitch which is consistent with some of the state-of-the-art earth sensors that are becoming available. The disturbance environment was computed based on models of the earth's gravitational and magnetic fields and the atmospheric density for solar maximum conditions. The residual magnetic dipole on the spacecraft was also assumed to be conservatively large at 1.0, 0.2 and 1.0 A-m^2 about roll, pitch and yaw axes respectively.

For earth pointing missions, the spacecraft pitch dynamics decouples from the roll-yaw dynamics which allows the pitch controller to operate separately from the roll-yaw controller (note that the roll and yaw dynamics remain gyroscopically coupled due to the momentum bias). The pitch control law used can be expressed as

$$M_y = -K_p a_y - K_d \dot{a}_y$$

where K_p and K_d are the proportional and derivative gains respectively, and a_y and $\dot{a}_y$ are the pitch angle and pitch rate, and M_y is the control torque about the y axis (i.e., pitch axis). The pitch rate $\dot{a}_y$ is estimated using a finite difference scheme:

$$\dot{a}_y = \frac{a_y - a_y^{pre}}{\Delta t}$$

where a_y^{pre} is the pitch angle at the previous sampling time and Δt is the controller time step. A direct output feedback controller structure is used for the roll/yaw controller which can be expressed as follows:

$$\begin{Bmatrix} M_x \\ M_z \end{Bmatrix} = [F] \begin{Bmatrix} a_x \\ w_x \\ w_z \end{Bmatrix}$$

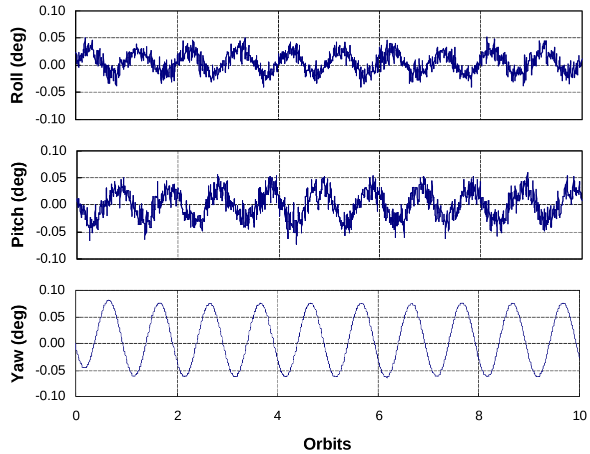

Figure 8 Computer simulation result of the GyroWheel based ACS performance.

where $[F]$ is the feedback gain matrix; a_x is the roll angle measurement from the earth sensor, and w_x, w_z are the inertial rates of the spacecraft measured by the GyroWheel about x and z body fixed axes (i.e., roll and yaw axes), respectively. This type of control structure is attractive as no attitude determination algorithm is required to compute the control commands. This keeps the attitude control algorithm very simple and reliable and minimizes the processing load on the spacecraft controller. The simulation results for the pointing performance of the earth pointing mode are given in Figure 8.

Note that the attitude performance can be maintained to better than 0.1 degrees in all axes including yaw without making a direct yaw measurement. For many missions, this would be all that is required and a yaw estimate would not be required except for diagnostic information or for use by the payload on-board the spacecraft.

The above discussion of the GyroWheel based ACS concept has shown how the GyroWheel can be used for attitude control of a LEO earth pointing spacecraft. However, this is also similar to an implementation for GEO spacecraft, although initial attitude acquisition manoeuvres and momentum dumping operations would be carried out using thrusters. However, for GEO missions, the GyroWheel can also be used during the transfer orbit stage when the spacecraft is slowly spun up to minimize thrust misalignment errors. The GyroWheel can be used to provide nutation control of the spacecraft spin axis during this operational mode. This can be done by either ensuring that the orientation of the GyroWheel is along the thrust vector, or if it requires to be perpendicular to the thrust vector, then 2 GyroWheel's can be placed back to back and both spun-up to near the tuned speed (fully redundant wheels and gyros are often flown in GEO spacecraft). This will allow controlling the total momentum near zero while still providing the rate sensing capability and the torqueing capability needed for active nutation damping.

Conclusions

Spacecraft ACS systems generally use the control of internal momentum to control their attitude. The GyroWheel is a new and novel device that provides the needed momentum bias to a spacecraft, imparts control torques about all three axes, and measures the spacecraft rates about two axes. In effect, the GyroWheel is a double gimbal momentum wheel with a unique spinning flex-gimbal mechanical suspension system for the rotor that allows it to also function as a precise rate gyro. A GyroWheel based ACS implementation was also described that combines the GyroWheel with a 2-axis earth sensor to provide a simple and very cost effective ACS implementation solution that can provide fine pointing control in all axes. The key benefits and features of the GyroWheel and the associated ACS are summarized as follows:

- for typical fine pointing ACS applications, a single GyroWheel can replace 3 standard momentum wheels (or if redundancy is required, 2 GyroWheels can replace 4 momentum wheels)
- uses momentum bias to reduce risk and extend design life of the bearings
- gimbal designed for infinite life and has built-in stops to handle launch loads
- rate sensing ability removes the need for direct yaw measurement and can provide high bandwidth attitude data during maneuvers (e.g., station keeping)
- the GyroWheel allows for significantly reduced mass, power and costs for a fine pointing ACS system
- can be used for both the transfer orbit and on-station attitude control modes of a GEO spacecraft

A fully functional prototype has been developed and testing has been conducted that demonstrated both the actuator and rate sensing functions of the device.. The GyroWheel offers a new ACS implementation strategy for earth pointing missions that can help to significantly reduce the spacecraft costs.