A NEW ATTITUDE CONTROL MECHANISM FOR LEO SATELLITES

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Abstract

ORBCOMM is a LEO communications spacecraft, providing global point to point packet messaging. Two are in operation now, and the rest of the (eventually 36) constellation design spacecraft are currently in integration and test. The ORBCOMM ACS mission is to point a communications antenna to nadir, while maintaining continuous Sun tracking via spacecraft yaw maneuvers. This mission is achieved using almost entirely magnetic control, providing a new standard of performance for this type of system.

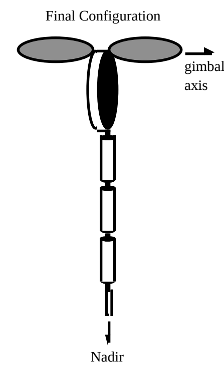
OSC's new design includes substantially improved attitude determination and control relative to the first two spacecraft. Using knowledge gained from the on orbit performance of Microlab 1, and ORBCOMM 1 & 2, both algorithms and hardware design have been augmented to provide accurate pointing without adding any mass. A unique new attitude determination and control architecture and supporting actuators were developed to meet these severe objectives. Accuracy is more than doubled, robustness to sensor and actuator failures (though there have been none so far) is added and autonomy is increased. Perhaps most important, tolerance to magnetic disturbances has been increased threefold, replacing manufacturing restrictions and complexity with onboard estimation.

Since substantial gains have been made through improved algorithms, some of these benefits are retroactively available to the spacecraft already on orbit. Further, these improvements enable a new class of spacecraft bus that provides *three* axis pointing in a 60 lb. weight class "core vehicle." OSC hopes to use this new core vehicle to provide flexible control systems support to a family of spacecraft, hosting a variety of sensor payloads. This paper describes the hardware and algorithms used to achieve the ORBCOMM Constellation mission: it specifically provides a reference example for effective nadir pointing, yaw steering spacecraft design, using substantially magnetic controls.

The ORBCOMM Spacecraft and ACS Mission

ORBCOMM is a lightweight, low Earth orbit satellite constellation providing global messaging service. Each spacecraft forms a packetized communications link between a remote subscriber terminal and a "gateway Earth station" which provides access to landline communications. In support of this mission, the attitude control system onboard ORBCOMM spacecraft is tasked to autonomously point a body fixed communications antenna to nadir.

The spacecraft is shaped like a hockey puck, with two circular solar panels that deploy out 90 degrees from either face of the puck. With the antenna pointing to nadir and the disk oriented vertically, edge on to the Sun, the solar panels can be articulated about the spacecraft y axis to track the Sun. The figure at right gives a general spacecraft layout, showing the antenna and solar panel configuration.



Three of these spacecraft are in 775km, 70 degree inclination orbit now, two carrying the ORBCOMM communications payload, while a third "Microlab," carries multiple scientific payloads. Though the missions, mass properties and operating modes are different, they use the identical ACS. A description of this ACS and its performance is given in references 1 and 2.

The ORBCOMM constellation will comprise 34 additional spacecraft in 108 and 45 degree inclination orbits, providing near continuous world-wide communications services. For the constellation spacecraft, significant attitude control system (ACS) and attitude reference system (ARS) performance enhancements have been made. These enhancements are the subject of this paper.

Comparison of Initial and Constellation ADCS Designs

The primary differences between the initial and constellation ORBCOMM ACS designs are the addition of a vertically oriented reaction wheel and incorporation of residual magnetic dipole states in the attitude estimator. The improvements are mass neutral, because addition of the reaction wheel made possible the removal of an equal amount of gravity gradient mass. The following table

Parameter	Budget/Spec	Original ACS	New ACS
Nadir Pointing Accuracy	5 deg CEP	4.5 deg CEP	2 deg CEP

summarizes top level ACS performance requirements for the ORBCOMM spacecraft, and compares predicted performance for the original and new (constellation design) ACS. Performance of the original design has been validated with on-orbit data, so confidence in the simulation predictions for the new ACS is high.

In the table above, note the original ACS successfully pointed the communications payload to nadir with a 4.5 degree CEP (Circular Error Probable: the median of all error samples) However, it did not fully meet its yaw pointing requirement, averaging 8% less power available than originally planned. Occasional transients to 70% of available power generation have been observed. By comparison, the new design easily meets all requirements, thanks in large part to the addition of the reaction wheel. The expected worst case still provides 95% of available solar power. Simultaneously, it allows greatly relaxed magnetic cleanliness requirements, a change that simplifies the necessary preflight calibration procedures.

Reaction Wheel

A special reaction wheel design was commissioned for the ORBCOMM mission. Seeking to use long estimator time constants, the ARS estimator operates with a presumption of low process noise. This in turn requires that the torques applied to the spacecraft be well known. A reaction wheel was sought that would provide accurate torque inputs over the same dynamic range as the 5 Amp-m^2 torque rods, implying a torque lsb of only 1e-6 nt-m. Rather than implementing precise torque control, the requirement is met by closing a speed loop within the wheel, translating torque commands into wheel acceleration commands. A very accurate speed control loop is needed to deliver good ramp response on such a small scale. Speed control loop accuracy of one RPM or better under all command trajectories is needed. Another key constraint: because of ORBCOMM's extremely light weight, the total mass budget for the wheel (including controller electronics) is just 0.63 kg.

Two vendors, Teldix and Tecstar, proposed compliant designs, and both have delivered functional prototypes for engineering development at this time. Though the two vendors chose unique and proprietary approaches to some aspects of the problem, both designs share onboard digital signal processors to implement the speed control loops, and high accuracy angular measurement of wheel position. Key parameters from the reaction wheel specification are included in the following table:

Attitude Reference System Modifications

The attitude reference system estimator includes two new features for the constellation design: an accounting for the dynamics introduced by the reaction wheel and additional states to estimate components of the spacecraft's residual magnetic dipole. A derivation of the original estimator algorithms is contained in reference 1, and so only the results are repeated here. The original A matrix propagated six states: the angular error about local level axes, and body inertial angular rate, in body coordinates. With the state vector ordered as $x=[d\theta,d\omega]^T$ the four submatrices are:

Reaction Wheel Specification

Parameter	Value	Units
Momentum	+/- 0.04	nt-m-sec
Rotor Speed	~1500	rpm
Rotor Inertia	~0.00025	kg-m^2
Torque	0.0050	nt-m
Torque Accuracy	1.00E-06	nt-m
Lifetime	5	years
Power	1.5	W
Mass	0.6	Kg
Speed control loop	~1	rpm
Hcmd error	3.00E-05	nt-m-sec
Ctl. loop bandwdth.	0.5	rad/sec
Interface	RS-422	
Dimensions	90x100	mm

$$A_{1,1} := -C_{bl}\cdot \mathrm{curl}(\omega) \qquad A_{1,2} := C_{bl}$$

$$A_{2,1} := 3\cdot\Omega^2\cdot\begin{bmatrix}(C_{lb}\cdot r)\times J\cdot C_{lb} \ldots \\ +(-J\cdot C_{lb}\cdot r)\times C_{lb}\end{bmatrix}\cdot \mathrm{curl}(r)$$

$$A_{2,2} := \begin{bmatrix} 0 & (j_y - j_z)\cdot r & (j_y - j_z)\cdot q \\ (j_z - j_x)\cdot r & 0 & (j_z - j_x)\cdot p \\ (j_x - j_y)\cdot q & (j_x - j_y)\cdot p & 0 \end{bmatrix}$$

...where [J] is the inertia tensor, [r] is a unit vector along the spacecraft position vector, [p,q,r] are components of the body rate, and C_{bl} rotates a vector from local level to body coordinates. The "curl" notation indicates a skew symmetric matrix that implements the vector cross product.

Estimated C_{bl} and [p,q,r] (vs. true values) are used in the flight code to calculate these matrices. Because the A matrix is time varying, it is recomputed and discretized onboard at 1/10 Hz for use in error covariance propagation. State estimates themselves are propagated using the full nonlinear equations at 1/2 Hz.

Residual dipole is modeled as an unknown vector constant, so the dynamics are augmented with another three states. Since the residual dipole crosses with the ambient magnetic field to produce torque on the spacecraft, angular acceleration is affected. Thus the equations for body rate error are augmented with terms comprising the inverse of the inertia matrix times the curl of B.

With dipole terms, there are now 9 states in the estimator altogether:

$$(x) := \begin{bmatrix} d\theta \\ d\omega \\ dH \end{bmatrix} \begin{matrix} \text{attitude wrt local leve} \\ \text{body rate errors} \\ \text{magnetic dipole} \end{matrix}$$

The augmented state traansition matrix includes all terms from the original design, plus increments resulting from addition of residual dipole error estimates and reaction wheel precession torques.

$$A_{new} := A_{original} \cdot \delta A$$

To calculate δA, Euler's equation is first written to explicitly include reaction wheel angular momentum.

$$\frac{d}{dt}\omega_b := J^{-1} \cdot \left[\vec{T} - \omega_b \times \left(J \cdot \omega_b + J_{wheel} \cdot \Omega spin \right) \right]$$

Then, torque terms arising from residual dipole are explicitly included (BxH), and partials are taken with respect to all the states. New terms resulting from the reaction wheel and the residual magnetic dipole are:

$$\delta A := \begin{bmatrix} 0 & 0 & 0 \\ 0 & J^{-1} \cdot \text{curl}\left(J_{wheel} \cdot \Omega_{spin} \right) & J^{-1} \cdot \text{curl}\left(\vec{B} \right) \\ 0 & 0 & 0 \end{bmatrix}$$

where...

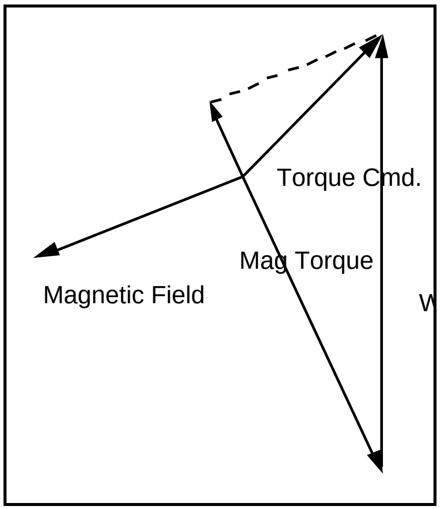
$$\text{curl}(r) := \begin{bmatrix} 0 & -r_z & r_y \\ r_z & 0 & -r_x \\ -r_y & r_x & 0 \end{bmatrix}$$

Finally, measurements from a Sun sensor are allowed for. A primitive Sun sensor is manufactured from six solar cells arrayed around the perimeter of the spacecraft, and used to aid in initial attitude acquisition before Earth sensor operation begins. Since it produces a vector measurement, the H matrix computations are identical to those already implemented for magnetic field vector measurement updates. This completes the description of modifications necessary to incorporate the reaction wheel and the residual magnetic dipole into the estimator. Estimator performance has been tested with residual biases up to 0.65A-m^2 in each axis (roughly 3 times the tolerance of the original design) with good success.

The estimator's calculated residual magnetic dipole is fed back into the ACS for cancellation with torque rod commands. Larger magnetic dipole tolerance allows for a relaxation in the magnetic calibration procedure that must be performed on every spacecraft prior to flight. A detailed magnetic budget apportions residual magnetic dipole error to many sources, each of which is taken into account in the calibration process. Calibration occurs in a zero gauss chamber with either zero or precisely controlled ambient magnetic field. Hard magnets are installed to counteract the residual spacecraft field, and the process is repeated until the measurements correspond to magnets too small to easily emplace. This final residual is programmed into a vehicle specific calibration data file, and becomes a permanent feed-forward into the ACS. A similar procedure is followed to detect and eliminate the residual soft iron tensor. Identification and neutralization of current loops induced by the different power loading states of the spacecraft was more difficult, and is made unnecessary by the incorporation of the dipole estimator.

ACS Modifications

The primary controller modifications result from the incorporation of the reaction wheel. The wheel's purpose is to allow the ACS to generate torque in an arbitrary direction. Using exclusively magnetic torque, the original design can only generate torque in a two dimensional space perpendicular to the instantaneous magnetic field vector. Continuous three dimensional control space is provided by the combination of reaction wheel and magnetic torques. Illustrated below is an example of this idea. Though not orthogonal, the vector sum of magnetically accessible and reaction wheel torques can always generate the desired torque command. For comparison on the same plot, the best possible magnetic only torque is drawn for the same situation. Note the torque error vector (dashed line) that results.



Wheel speed is constrained via addition of a wheel speed control loop. Wheel RPM is commanded to zero, but at a lower priority (gain) than the attitude control loops. An integral path is included in the wheel speed controller because, while torque demand typically varies widely an orbit, rectification can occur, causing a significant net wheel momentum gain over a period of several orbits. The integrator trims this net torque, producing zero mean wheel speed.

So, there are four torque commands altogether; pitch, roll, yaw and wheel despin, and only three degrees of freedom: two dimensions of magnetic torque and one wheel. Changing geometry between the magnetic field vector and the wheel spin axis continuously varies the way that magnetic and reaction wheel command inputs span the torque control space. In pathological situations, only a two dimensional spacecraft control is available. This occurs briefly twice per orbit when the spacecraft passes through the magnetic equator: then the magnetic field is perpendicular to the vertical wheel spin axis, and the wheel torque lies in the same plane as the magnetically available torque. In this situation, no roll torque can be generated, but wheel despin can be achieved by opposing a reaction wheel torque with a magnetic yaw torque. To smoothly and continuously make the tradeoff between wheel speed and spacecraft attitude control, a least squares algorithm continuously apportions the four torque commands to the three actuator output signals. The equations below show how the four torques are generated as a consequence of the three available controls: WheelTrq, MagTrq1 and 2. The two magnetic torques act along vectors described as bp1 and bp2, which are body components of a vector basis for the planar space perpendicular to the magnetic field (b-field). The [A] matrix is not full rank, so a pseudoinverse must be used to solve for the 4 element delivered torque vector:

$$\begin{bmatrix} bp1_x & bp2_x & 0 \\ bp1_y & bp2_y & 0 \\ bp1_z & bp2_z & -1 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} MagTrq_1 \\ MagTrq_2 \\ WheelTrq \end{bmatrix} = \begin{bmatrix} Tcmd_x \\ Tcmd_y \\ Tcmd_z \\ T_{despin} \end{bmatrix}$$

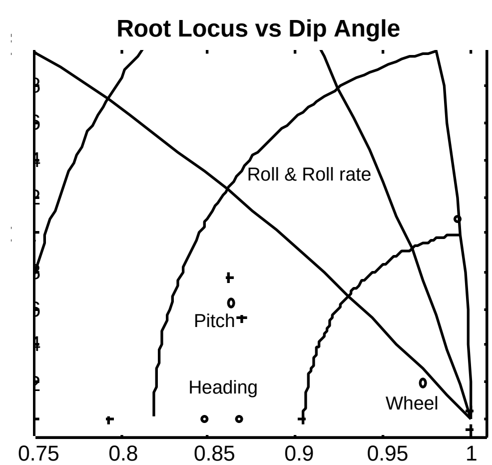
or.... $A\cdot\left(Control_{output}\right) = T_{cmd}$

The best solution is the pseudoinverse...

$$T_{delivered} = A\cdot\left(A^T\cdot A\right)^{-1}\cdot A^T\cdot T_{cmd}$$

The equations may be further augmented to include three control costs each acting on one of the control inputs. This is achieved by simply appending Kcost*eye(3) to the bottom of [A]. In this implementation, the cost “commands” are set to zero, becoming an additional constraint set. This implementation softens the response in nearly singular situations when large but nearly opposing magnetic and wheel torques would otherwise be commanded simultaneously in order to produce a small resultant. The difference of two such large quantities is impractical with realistic actuator dynamic ranges, hence to be avoided.

Small pitch or roll torque disturbances are generated as a consequence of removing excess reaction wheel momentum. This is because the magnetic wheel unloading torque does generally



couple into the pitch or roll axes, and a natural result of the overdetermined nature of the torque command equations. Consequently, some gravity gradient is still required to counteract this secular disturbance. With gravity gradient linear analysis will show that all the states can be simultaneously controlled.

Feedforward terms for the euler cross coupling torques, the reaction wheel precession torque, and feedback of calculated residual magnetic torque all act to reduce disturbance inputs to the controller. With these feed-forwards proportional and rate controllers on the spacecraft attitude states can effectively control attitude is to within the accuracy of the estimator.

Linear Analysis

A frozen point linear analysis allows gain selection and assessment of the system stability at any fixed geometry. The preferred approach is *z*-domain pole placement, and one such result is shown here. In the figure, the discretization time step is 60 seconds, a large number chosen to demonstrate the potential to operate the ACS at a lower frame rate. (The nominal time step is 2 sec.) Gains have been specially chosen for clarity in this example, but flight gains will be similar. The plot shows a parameter sweep indicating pole motion as a function of changing magnetic field geometry. The dip angle of the magnetic field is varied from zero ("o") to 90 degrees ("+") as would typically occur during a quarter period in a polar orbit. In fact, it is useful to visualize the dynamics varying back and forth between the ends of the root loci as the spacecraft orbits the Earth. Magnetic dip is by far the largest affect on the control system, and hence an important case for study. The primary component of each root was identified via the eigenvectors, and is labeled on the plot. There are several points worth noting: First, at the extrema of the dip angle trajectory, there is always a pair of undamped roots. These represent the roll angle at the "magnetic equator", and the reaction wheel near the north and south poles. Over the poles, no magnetic torque is available for yaw steering, so all vehicle control must come at the expense of the reaction wheel. Similarly, the reaction wheel can never generate any pitch or roll torque, and at the equator, when the Earth's field is horizontal, neither can the magnetics. At that point we see just the oscillatory gravity gradient mode.

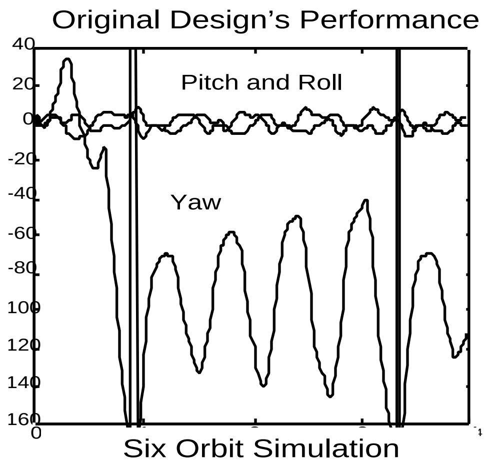
Simulated Performance

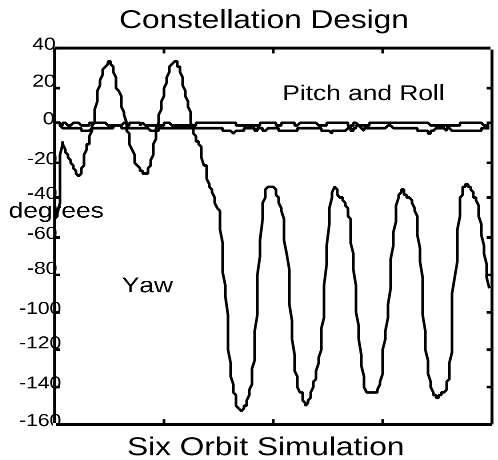
Performance of the ORBCOMM ACS is studied with a full non-linear simulation that models spacecraft dynamics, sensor and actuator performance, and significant disturbance sources. Primarily these are orbit geometry, residual magnetic dipole (hard and soft iron effects) solar pressure disturbances, and errors in the magnetic field model. All of these effects degrade attitude estimator and controller performance. The impact of orbit geometry is difficult to overstate. The yaw command trajectory directly sets the torque demand, but the magnetic field vector direction in local level coordinates and it's phase relationship with yaw commands determine what combination of magnetic and wheel torque inputs will be needed. Simultaneously, the estimator performance is primarily affected by the verticality of the magnetic field: large dip angles reduce observability, demanding attitude and rate state propagation without good measurements when the spacecraft overflies the magnetic poles.

This happens to ORBCOMM for several orbits once each day. (Reference 2 gives a good example of this effect, and a detailed discussion of its consequences.) Therefore, simulation studies typically address a large set of geometries, and a statistical distribution of key sensor, actuator and residual dipole errors. Results shown here indicate typical performance in the presence of expected residual dipoles and moderately difficult geometry. The plots show pitch, roll and yaw angles over a six orbit time period.

Both constellation (new) and original ACS simulations are shown. The runs have identical input conditions, except the constellation run suffers from *more than 3 times* greater residual magnetic disturbances. Note the smooth sinusoidal yaw trajectory, and small pitch and roll angles produced by the new design. The solar array pointing effectiveness is greater than 98%, and the nadir pointing CEP is better than 2.5 deg. The marked change in yaw command bias from zero to -90 deg after the second orbit is a yaw command mode change. The performance cannot be directly compared, because under conditions of large residual dipoles, the old design tumbles. Clearly the ACS changes have provided substantial improvement.

Summary/Conclusions:





Use of a single, vertically oriented reaction wheel, along with very mild gravity gradient assist has been shown to provide good three axis pointing in a LEO spacecraft application. The implementation provides more flexibility than momentum bias systems, and can tolerate large magnetic disturbances via estimation. Critical to the implementation is a small reaction wheel with precise torque command tracking capabilities. The reaction wheel is used to provide three dimensional capability. The ORBCOMM ACS mission is fully supported, and OSC hopes other future spacecraft will benefit from this architecture. This design will be demonstrated on orbit early next year.

References

[1]Krebs, Mark R, *ORBCOMM: Lessons Learned on a Crash Program,* AAS-96-078.

[2]Stoltz, Paul M.; Krebs, Mark R.; and Baltman, Richard, *ORBCOMM Attitude Determination and Control,*. AIAA 96-3620.

[3]Krebs, Mark R., *A One Wheel Solution to Attitude Control*, OSC Memo, 8/27/93.