An On-board Algorithm for Automatic Sun-pointing of a Spinning Satellite

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Abstract

Autonomous control of the orientation of the rotation axis of a spin-stabilised satellite is a desirable feature for small projects in order to reduce the need for support from the ground. Spin stabilisation is mostly used in space plasma physics satellites, both to keep wire booms taut but also make particle sensors scan in various directions. Two different orientations of the spin axis are common; perpendicular to the orbital plane (cartwheel) or Sun-pointing.

Simple on-board control algorithms using magnetic actuators can be used for both orientations. For the cartwheel orientation (spin axis aligned to the orbit normal) the classical "minus-B-dot" law can be used in high inclination orbits to automatically control the satellites' spin axis. In this algorithm the projection of the Earth's magnetic field along the spin axis is measured. The sign of the time derivative of this measurement is used to determine the polarity of the magnetic dipole moment of a magnetic torque coil with its dipole moment aligned with the spin axis. By applying this control law the spin axis aligns with the orbit normal[1].

A simple control law algorithm for automatically pointing the spin axis in the direction of the sun using a sun-sensor, a magnetometer and magnetic actuators is also possible. A Swedish patent application (no. 9702333-7) for this algorithm has been submitted. The principles of this control law are described in this technical note.

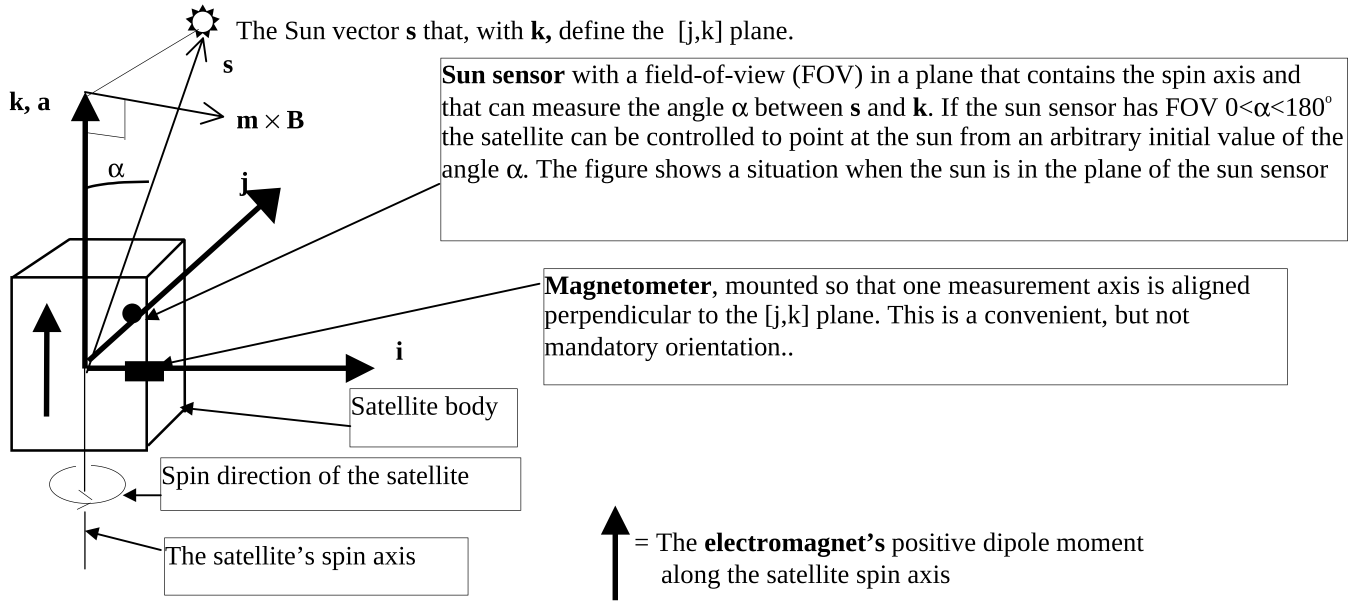

Figure 1 Orientation of sensors and actuators

Earlier methods to point the spin axis of a satellite in the direction of the sun have been based on a two-stage process: 1) the determination (on board the satellite or on the ground) of the orientation of the spin axis in inertial co-ordinates using e.g. a sun sensor and a magnetometer; 2) computation onboard the satellite (or on the ground) of the suitable current direction through the electromagnet and the instants of reversing this direction so that the interaction of the electromagnet with the Earth's magnetic field would turn the spin axis towards the sun. The disadvantage with this traditional method is that it requires the explicit computation of the orientation of the spin axis in inertial co-ordinates. The method described here requires that neither orientation of the spin axis nor the sun in inertial co-ordinates need to be determined or known. The present method uses a sun sensor, a magnetometer and an electromagnet, the magnetic dipole moment of which is parallel or anti-parallel to the spin axis and can change sign when the current through the electromagnet is reversed. The angle between the spin axis and the direction of the sun need to be measured onboard the satellite. The direction of the current through the electromagnet shall be such that the magnetic dipole moment of the electromagnet along the spin axis has the same sign as the component of the earth's magnetic field along an axis perpendicular to the plane defined by the spin axis and the direction towards the sun. Only a simple logic, implemented in hardware or software, is needed onboard the satellite. The sun sensor provides an indication when the sun passes through the plane in which its field-of-view is defined and this indication defines this plane. The sun sensor also measures the angle between the spin axis and the direction to the sun. The following quantities are used below in the derivation of this control law:

a the spin axis orientation (unit vector). **a** is parallel to the unit vector **k**.
B the Earth's magnetic field (vector)
B the scalar magnitude of the Earth's magnetic field
b a unit vector parallel to the earth's magnetic field vector with components b_x , b_y, b_z where the axes x,y,z correspond to unit vectors **i,j,k.**
i,j,k are unit vectors in a Cartesian co-ordinate system with the origin on the satellite's spin axis. The [j,k] plane is defined by the spin axis and the direction to the sun (unit vector **s**).
L the satellite's angular momentum (vector)
L the scalar magnitude of the satellite's angular momentum
M the magnetic dipole moment vector of the electromagnet
m a unit vector parallel to the magnetic dipole moment vector of the electromagnet
s direction to the sun (unit vector)
T the torque vector acting on the electromagnet due to its interaction with the Earth's magnetic field
T the scalar magnitude of the torque vector acting on the electromagnet due to its interaction with the Earth's magnetic field
t a unit vector parallel to the torque vector acting on the electromagnet due to its interaction with the Earth's magnetic field
u the polarity of the dipole moment of the electromagnet

The control law is based on that:

- the sun sensor is designed such that it has a field-of-view in a plane directed out from the spin axis (and parallel to the spin axis) and provides an indication when this field of view passes the [j,k] plane. (See Figure 1)
- the sun sensor measures the angle α between the direction to the sun and the satellite's spin axis when its field-of-view passes the [j,k] plane. (The sun angle α is larger than zero by definition.)
- the magnetometer is designed such that it can determine the sign of the component of the earth's magnetic field perpendicular to the plane defined by the spin axis and the direction to the sun (the [j,k] plane).
- the satellite is equipped with an electromagnet the magnetic dipole moment of which, **M** (unit vector: **m**), is parallel or anti-parallel to the spin axis can change sign if the current through the electromagnet is reversed, i.e.

$$\mathbf{m} = u\,\mathbf{k} \qquad \textit{(1)}$$

Where u = { the polarity of the dipole moment of the electromagnet } = ± 1.

A unit vector parallel to the Earth's magnetic field is called **b** and has the components b_x , b_y, b_z where the axes x,y,z correspond to the unit vectors **i,j,k**. The scalar magnitude of the Earth's magnetic field is called B.

From elementary electrodynamics we know that the electromagnet is subject to a torque **T** the direction of which (unit vector **t**) is the vector product of magnetic dipole moment vector and the magnetic field vector of the Earth:

$$\mathbf{T} = T\,\mathbf{t} = B\,\mathbf{m} \times \mathbf{b} = u\,B\,(0,0,1) \times (b_x\,,\, b_y,\, b_z) =$$
$$= u\,B\,(-b_y,\, b_x,\, 0) \qquad \textit{(2)}$$

The spin motion of the satellite is assumed to take lace without nutation or other deviations from a pure rotation. The angular momentum, **L**, of the satellite is then assumed to be:

$$\mathbf{L} = L\mathbf{a} \qquad \textit{(4)}$$

Classical mechanics states that angular momentum should be conserved, i.e:

$$d\mathbf{L}/dt \equiv \mathbf{T} \qquad \textit{(4)}$$

T is always perpendicular to **L** since $\mathbf{L}\bullet\mathbf{T}=$ $=BL\mathbf{a}\bullet(\mathbf{m}\times\mathbf{b})=\{\mathbf{a}$ and $\mathbf{m}$ are parallel$\}=$ $=BL\mathbf{a}\bullet(\mathbf{a}\times\mathbf{b})\equiv 0$. So, the scalar magnitude of the angular momentum is not changed by the torque of the electromagnet, only its direction. Thus, (4) can be rewritten:

$$L\,d\mathbf{a}/dt \equiv \mathbf{T} \qquad \textit{(5)}$$

One can visualize the time derivative of the spin axis vector as a vector originating from the tip of **a** with the scalar magnitude T/L, i.e d**a**/dt can be said to make **a** turn around an axis defined by $\mathbf{a} \times d\mathbf{a}/dt$. If this vector has a component parallel to the normal of the plane defined by **a** and **s** the vector **a** tends to align with **s** and α is reduced. The expression for the normal is $\mathbf{a} \times \mathbf{s}$. The condition that $\mathbf{a} \times d\mathbf{a}/dt$ and $\mathbf{a} \times \mathbf{s}$ must be as parallel as possible can be expressed by stating that they must not have any component that is antiparallel (a vector **p** is antiparallel to the vector **q** if **p** = -**q**), i.e.:

$$(\mathbf{a} \times d\mathbf{a}/dt) \bullet (\mathbf{a} \times \mathbf{s}) > 0 \qquad \textbf{\textit{(6)}}$$

In this equation

$$\mathbf{a} \times \mathbf{s} = (0,0,1) \times (0, \sin\alpha, \cos\alpha) = \\ = (-\sin\alpha, 0, 0) \qquad \textbf{\textit{(7)}}$$

and

$$\mathbf{a} \times d\mathbf{a}/dt = \mathbf{a} \times (\mathbf{T}/L) = \\ = (0,0,1) \times u\,(B/L)(-b_y, b_x, 0) = \\ = u\,(B/L)\,(-b_x, b_y, 0) \qquad \textbf{\textit{(8)}}$$

Inserting (7) and (8) in (6) we obtain

$$(\mathbf{a} \times d\mathbf{a}/dt) \bullet (\mathbf{a} \times \mathbf{s}) = \\ = (-\sin\alpha, 0, 0) \bullet u\,(B/L)\,(-b_x, b_y, 0) = \\ = \sin\alpha\,(B/L)\,u\,b_x > 0 \qquad \textbf{\textit{(9)}}$$

Since B>0, L>0 and α>0 are always true statements this expression can only remain >0 ***if, and only if, u and b_x*** have the same sign.

Therefore the control law can be formulated:

The passage of the field-of-view through the [j,k] plane is used to determine the sign of the Earth's magnetic field in a direction, **i** , perpendicular to the [j,k] plane (**i,j,k** are unit vectors in a Cartesian coordinate system with the origin on the spin axis of the satellite). The direction of the current through the electromagnet shall be such that its magnetic dipole moment along the satellite's spin axis ($\mathbf{a} \equiv \mathbf{k}$) has the same sign as the component of the Earth's magnetic field along the axis **i**. If the magnitude of this component is very small the current through the electromagnet is turned off.

The control law remains in effect until the measured value of α has decreased to the desired value, e.g. the smallest value when the suns sensor still provides a sufficiently accurate indication of when its field-of-view passes the [j,k] plane (when $\mathbf{s} \equiv \mathbf{a}$ the [j,k] plane is not defined). This control law is implemented in logic onboard the satellite than can read out the sun sensor and the magnetometer and controls the current through the electromagnet.

References

[1] Hodgart M.S., •Attitude control and dynamics of UoSAT angular motion•, The Radio and Electronic Engineer, Vol. 52, No. 8/9, pp 379-384, August/September 1982.