

DEVELOPMENT OF A SYSTEM FOR ATTITUDE ESTIMATION OF ARTIFICIAL BOX-SHAPE SATELLITES USING PHOTOVOLTAIC PANELS AS SUN SENSOR

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Abstract. *It is necessary at least two or more independent known vectors for attitude determination of an artificial satellite. One of these vectors can be the Earth Magnetic Field, which is used as reference in navigation for centuries. Other reference can be the sun, which is easily distinguished of other astronomical objects in the proximities of the Earth. While the Earth Magnetic Field can be measured by a small solid-state three-axis magneto-resistive transducer, the own photovoltaic system of the artificial satellite can provide an evaluation of the azimuthal position of the sun. This paper presents a way to estimate the sun position from the own satellite power system. This information is used for attitude determination, allowing the integration of two important subsystems of an artificial satellite.*

Keywords: *Attitude Determination, Artificial Satellites, Photovoltaic System, Magnetometer*

1. INTRODUCTION

An artificial satellite is a component of a spatial system, an ample set of elements in the space (other satellites, spacecrafts, spatial stations, etc.) and in the ground (tracking stations, antennas, control centers, etc.). Since a satellite operates above of the Earth atmosphere, it provides the perspective of a general survey over great areas and global phenomena, as well allows several activities related to telecommunications and scientific researches in an environment with quasi-constant microgravity. Aiming the realization of a spatial mission, an artificial satellite transports several onboard equipments, such as radars, antennas, telescopes, photographic cameras, equipments for scientific measures, etc.

The power supply for onboard equipments has vital importance in an artificial satellite. Considering characteristics such as modularity, cost, maintenance and life, the photovoltaic generation is the more adequate energy resource for spatial applications. The electrical energy is obtained from the direct conversion of the luminous energy using photovoltaic cells, which are interconnected in series-parallel arrays to increase the energy capacity. Since the light-generated power in photovoltaic arrays is highly dependent of the intensity and direction of the incident sunlight, it is considerably variable in a satellite and must be conditioned and regulated by power electronic converters to supply onboard equipments.

The success of a spatial mission of an artificial satellite is determined by the interactions of the onboard equipments with others elements of the spatial system. An onboard equipment must be pointed to a specified aim to assure its perfect operation, obtaining a good power level and an improved signal-to-noise ratio of the received and transmitted data. Thus, these interactions are affected by the satellite attitude, its spatial position and orientation in relation to a specific aim. The satellite attitude related to Earth is shown in Fig. 1. The satellite attitude can be mathematically represented by any operator that rotates a vector inside of a coordinate system.

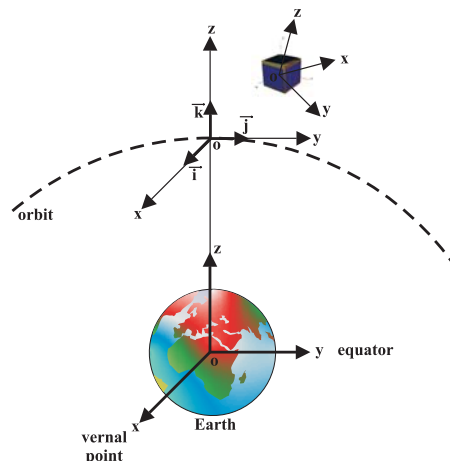


Figure 1. Satellite attitude related to Earth reference.

From the specific measurements, the satellite attitude related to an inertial reference can be estimated using deterministic or optimization methods. In the most of these algorithms for attitude computation, it is required the evaluation of at least two independent vectors with known directions. Several known vectors can be used as reference for attitude determination. One of these vectors is the geomagnetic field, a magnetic dipole aligned along the Earth’s rotational axis that points toward to magnetic north. The intensity of the geomagnetic field weakens with the altitude, restricting its use in the attitude determination for applications at low Earth orbits. Since the sun is easily recognized by any object near of the Earth, its azimuthal position related to artificial satellite can be considered as another possible reference vector for attitude determination.

This paper proposes the use of the own photovoltaic panels of the artificial satellite for evaluation of the azimuthal position of the sun. While the measure of the geomagnetic field is obtained from a three-axis magneto-resistive transducer, the sun position vector can be acquired from the operation of the power electronic converter. Both vectors are used to estimate the satellite attitude from a mathematical algorithm known as Q-method. Thus, two important subsystems of an artificial satellite can be integrated, providing various benefits always welcome in spatial applications, such as economy, redundancy, autonomy, etc.

2. PHOTOVOLTAIC GENERATION, POWER CONVERTER AND BATTERY MANAGEMENT

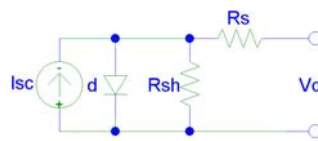


Figure 2. Equivalent electrical circuit of a photovoltaic cell.

A photovoltaic panel consists in series-parallel arrays of several photovoltaic cells, which are basically p-n diodes with the junctions positioned close to the top surface. The equivalent electrical circuit of a photovoltaic array is shown in Fig. 2. The series resistance R_s depends on the p-n junction depth, impurities and the contact resistance, while the shunt resistance R_{sh} is inversely related with leakage current to the ground. The light-generated electrical current I_{sc} depends on the efficiency of photovoltaic conversion and the incident power of the solar radiation over the photovoltaic panel, which can be approximated by the mathematical cosine model (Patel, 1999)

$$I_{sc} = I_{sc}|_{\beta=0^\circ} \cos \beta. \tag{1}$$

where the incidence angle β is defined in the Fig. 3. Since the electrical output in the real photovoltaic panels deviates significantly from the proposed cosine model for $\beta > 50^\circ$, this approach can lead to wrong calculations, which are the main source of inaccuracies in the determination of the sun positioning (Sityar, 1992; Patel, 1999; Winetraub *et al.*, 2005). For a better accuracy, it is recommended the use of other power-angle curves of the photovoltaic cell, such as the Kelly cosine shown in Fig. 4.

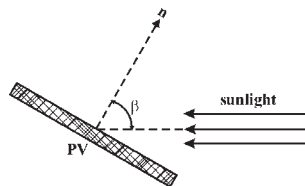


Figure 3. Definition of the sun light incidence angle β .

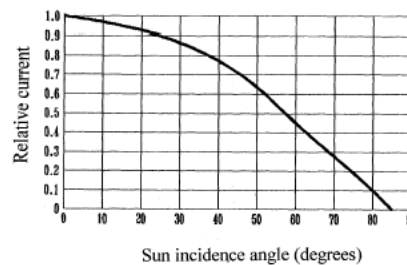


Figure 4. Kelley cosine curve for photovoltaic cell at sun angles from 0 to 90° (Patel, 1999).

The output current I is given by

$$I = I_{sc} - I_D \left(e^{\frac{V}{V_T}} - 1 \right) - I_{sh}, \quad (2)$$

where I_{sh} = shunt-leakage current, I_D = the reverse saturation current of the diode, V = cell voltage, and V_T = thermal voltage. Neglecting the current I_{sh} , which is very small in real cells, the open circuit voltage V_{oc} of photovoltaic panels is obtained when $I = 0$, resulting in

$$V_{oc} = V_T \log \left(\frac{I_{sc}}{I_D} + 1 \right) \approx V_{oc}|_{\beta=0^\circ} + V_T \log(\cos \beta). \quad (3)$$

Since I_{sc} is several orders of magnitude greater than I_D , V_{oc} is many times greater than the V_T and the voltage variation in a photovoltaic module with β is relatively low.

The power system of an artificial satellite generally uses a regulated voltage bus architecture and some form of direct energy transfer to condition power from the solar arrays. Due to its low and relatively constant heat dissipation, a power electronic converter widely used in satellite applications is the Sequential Shunt Regulator (SSR), which schematic diagram is shown in Fig. 5 (Shum and Ashley, 1996; Hewlett Packard Company, 1997; Garrigós *et al.*, 2006). The photovoltaic array is divided into several sections, where each module has its own dedicated switching device or circuit. The current I can either flow to the bus and supplies loads and batteries when the MOSFET switch is off, or be deviated, short-circuiting the photovoltaic module when the MOSFET switch is on. Since the light-generated currents by each module are summed by an OR connection of very fast diodes, only the photovoltaic module that generates the greatest amount of power actively supplies the bus. The average of the bus current I_{bus} is given by

$$\frac{I_{bus}}{I} = 1 - D, \quad (4)$$

where D is the switching duty cycle. Since the current in the bus is pulsed, a large capacitor filter is required to smooth current pulses and to reduce the voltage ripple. As the variations in the capacitor charge reflect the energy exchanges between photovoltaic arrays and electrical loads, the bus voltage must be controlled to adjust the demand of the electrical loads according to amount of power generated by photovoltaic arrays. This voltage control must be fast and accurate to assure the energy balance, restricting the voltage variations to acceptable limits that do not affect the performance of the onboard equipments. The voltage controller modulates the duty cycle of a PWM signal, which simultaneously drives all six MOSFET's switches of the SSR. Since the bus capacitance behaves as a big integrator, a simple proportional controller can be enough for a null error in the regulation of the bus voltage.

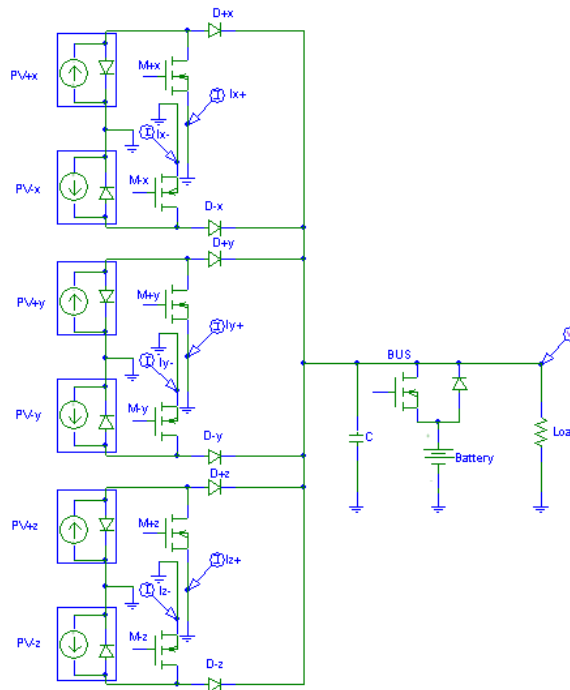


Figure 5. Sequential Shunt Regulator.

The battery operates in stand-by, assuming the load during eclipses, faults and eventual current peeks, when the voltage bus decreases and the series diode becomes directly polarized. A MOSFET switch can connect the battery to the power bus for its recharge when the satellite is illuminated again. The battery charge is monitored by a hysteresis controller that commands a MOSFET switch, which connects the battery to the power bus when its voltage level is the minimum. Aiming to preserve the useful life of the battery, it is disconnected from bus voltage when the maximum charge is reached.

3. ACQUISITION OF AZIMUTHAL POSITION OF THE SUN

A sun sensor is usually used to evaluate the azimuthal position of the sun in an artificial satellite. The architecture of this sensor can be based in photovoltaic cells, cameras or CCD image sensors (Winetraub *et al.*, 2005; Chen *et al.*, 2006). According to application, it is necessary to include several sun sensors in different places of the satellite (Falbel and Paluszek, 2001). If the information related to sun position is lost due to eventual satellite eclipses, a possible solution for attitude estimation is assume that the angular velocities of the satellite does not vary while the sunlight that reaches it is blocked by a body such as the Earth or other satellite (Winetraub *et al.*, 2005). Since the generated power by photovoltaic panels of an artificial satellite is highly dependent of the intensity and direction of the incident sunlight, an interesting possibility is its use to evaluate the azimuthal position of the sun (Sityar, 1992; Santoni and Bolotti, 2000; Viscito and Cerise, 2007).

Since the relationship between the angle of the incident sunlight over the photovoltaic module and its light-generated currents I_{sc} follows the cosine law presented in the eq. 1, the geometric inspection of an illuminated box shape satellite with a segmented photovoltaic array in six modules (one module for each side of the box) reveals that the components of a vector that points towards to sun are proportional to summation of the light-generated currents I_{sc} in opposite sides for a coordinate system constituted by the normal axes to the satellite surfaces, as illustrated in Fig. 6. Thus, the unitary vector that points towards to sun is given by

$$\hat{s} = \sin(\phi) \sin(\theta) \mathbf{i} + \cos(\phi) \sin(\theta) \mathbf{j} + \cos(\theta) \mathbf{k} = \frac{I_{sc+x} - I_{sc-x}}{I_{scx} |_{\phi=0^\circ, \theta=0^\circ}} \mathbf{i} + \frac{I_{sc+y} - I_{sc-y}}{I_{scy} |_{\phi=90^\circ, \theta=0^\circ}} \mathbf{j} + \frac{I_{sc+z} - I_{sc-z}}{I_{scz} |_{\theta=90^\circ}} \mathbf{k}, \quad (5)$$

where I_{sc+x} , I_{sc-x} , I_{sc+y} , I_{sc-y} , I_{sc+z} , and I_{sc-z} are the light-generated currents by the photovoltaic panels respectively located in the axes $+x$, $-x$, $+y$, $-y$, $+z$, and $-z$.

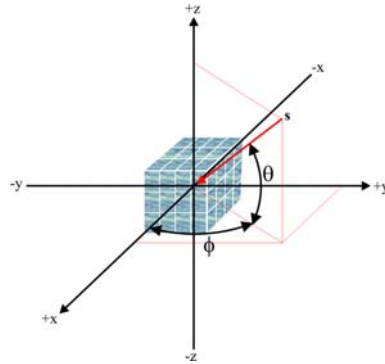


Figure 6. Incidence of the sunlight in a box shaped satellite.

The scheme for acquisition of azimuthal position of the sun from the SSR operation is shown in Fig. 7. Neglecting the diode and shunt-leakage currents, the light-generated current I_{sc} of a photovoltaic module can be evaluated when its output is short-circuited (Sityar, 1992). Thus, the components of the azimuthal position of the sun can be directly measured by a Hall current transducer when the shunt MOSFET is on. A Sample/Hold circuit, which S/H cycles are determined by the own gate signal of the shunt MOSFETs switches, samples the transducer signal when the shunt switches are on, and holds it while the MOSFET switches are off, assuring that the components of vector is always available for acquisition.

4. SIMULATION RESULTS

The acquisition of the vector sun position is verified from a computational simulation of the SSR using the SimPowerSystems package of the MATLAB/SIMULINK. It is considered that a box shape satellite which surface are covered by six photovoltaic arrays that generates $6 \times 10W_p$ at an irradiance of $1000W/m^2$. This satellite is rotating in the space at $\dot{\phi} = 1.26\text{rad/s}$ and $\dot{\theta} = 6.28\text{rad/s}$ (see Fig. 6). The sunlight irradiance in the space is considered $1367W/m^2$. The duty cycle D of the SSR is modulated by a PWM of 5kHz, and a capacitor of $1500\mu F$ is connected to power bus aiming to reduce the voltage ripples. A simple proportional controller, which gain is adjusted to 300, regulates the bus voltage, which reference is adjusted to 15V to supply a resistive load of 90Ω and a 12V battery. The acquisition of the azimuthal position

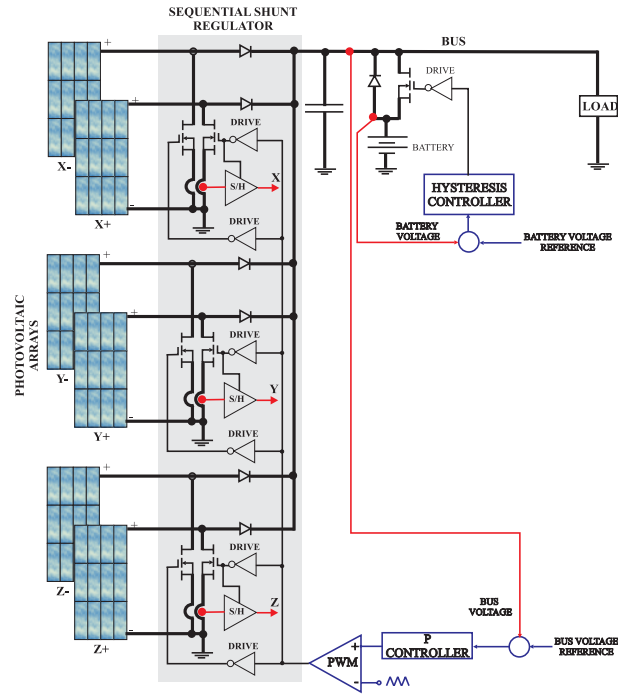


Figure 7. Scheme for acquisition of azimuthal position of the sun from the SSR and bus voltage regulation.

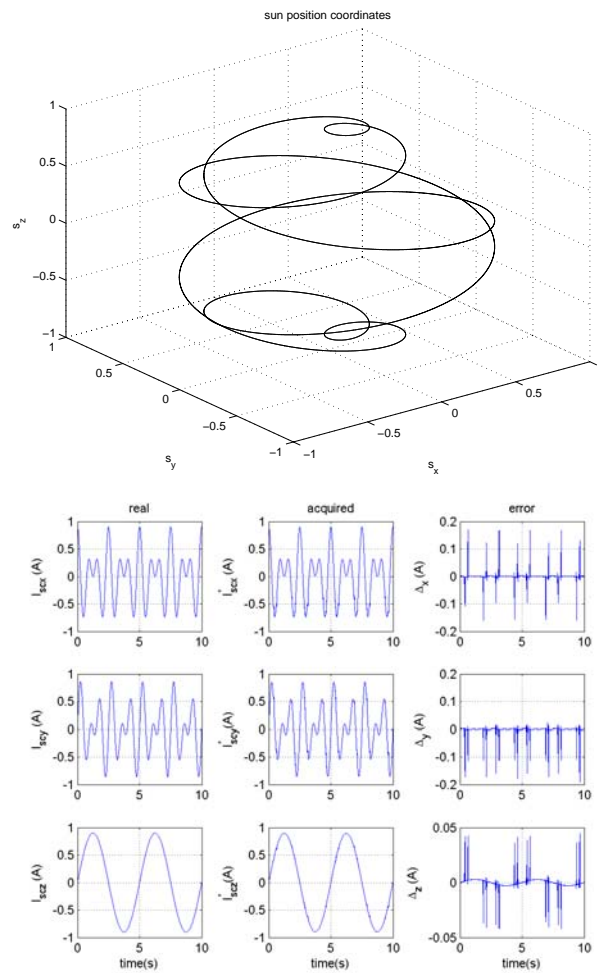


Figure 8. Acquisition of the azimuthal position of the sun.

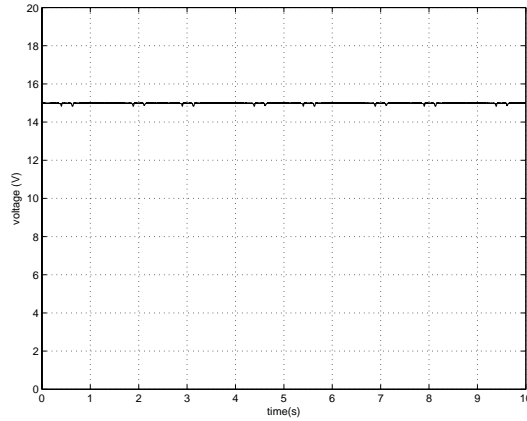


Figure 9. Regulated bus voltage in the Sequential Shunt Regulator.

of the sun is shown in the Fig. 8. It is observed that the error is small, basically caused by the sample operation, and can be minimized using a more efficient filter. The attitude motion (angular frequencies of the satellite) can be evaluated from the Fast Fourier Transform (FFT) of the acquired data. Although the photovoltaic power supply is highly variable due to satellite rotation, the proposed P controller is enough to assure a null voltage error, providing an excellent regulation of the bus voltage for the considered load, as shown in the Fig. 9.

5. MEASUREMENT OF GEOMAGNETIC FIELD

The geomagnetic field can be measured using a small solid-state three-axis magneto-resistive transducer Honeywell HMC2003 (Honeywell Inc., n.d.). It is constituted by thin strips of permalloy (Ni-Fe magnetic film) with sensitive electrical resistances to applied magnetic field connected in a Wheatstone bridge circuit. Thus, the output voltage signals of this transducer are proportional to the magnitudes of the three ordinal components of the measured magnetic field. The output voltage range of the Honeywell HMC2003 is 0 to +5V, where the reference value for the null intensity of the magnetic field is +2.5V. The measurement circuit for geomagnetic field is shown in Fig. 10, where the output voltage signals X, Y and Z can be connected directly to an analog-to-digital (A/D) converter while the +2.5V reference output can be used as the zero field reference voltage. In order to maximize the transducer resolution, a strong SET/RESET pulse must be occasionally applied to transducer via P and N channel MOSFET drivers to eliminate the effect of the past magnetic history and to avoid the degradation of the output signal.

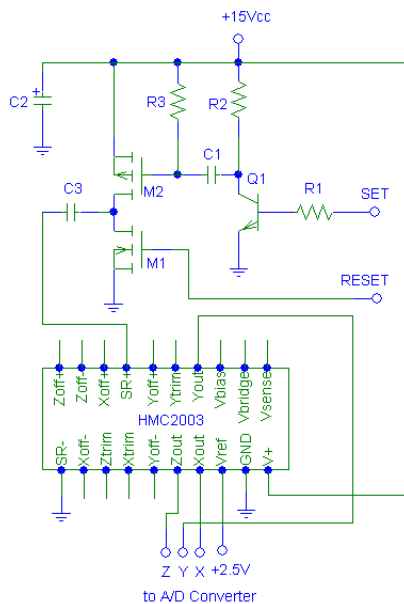


Figure 10. Magnetometer circuit.

6. ATTITUDE ESTIMATION: Q-METHOD ALGORITHM

The attitude of a body is basically represented by a vector \mathbf{n} , which defines the direction of the rotation axis, and a scalar, that specify the rotation angle α over this axis. A common way to specify the attitude is the use of the Euler's angles $\psi/\theta/\phi$, three independent parameters that represent three consecutive rotations in a convenient sequence around the axis of an inertial system. The combination of these rotations results in the attitude matrix \mathbf{A} , which represents the orientation of an object in relation to inertial coordinate system, and can be interpreted as an operator that rotates any vector inside of a coordinate system:

$$\mathbf{A}(\mathbf{n}, \alpha) = \mathbf{I} \cos(\alpha) + [1 - \cos(\alpha)]\mathbf{nn}^T + \tilde{\mathbf{n}} \sin(\alpha) \quad (6)$$

where \mathbf{I} is the identity matrix and $\tilde{\mathbf{n}}$ is the anti-symmetrical matrix constituted with the components of \mathbf{n} .

Considering a stipulated reference vector \mathbf{v}_i for each observed vector \mathbf{w}_i by one of the n sensors of the satellite, the rotation of a reference vector \mathbf{v}_i to obtain a second vector \mathbf{w}_i is described as

$$\mathbf{w}_i = \mathbf{A}\mathbf{v}_i, \quad (7)$$

where an estimative of the attitude matrix \mathbf{A} can be obtained from the minimization of the cost function:

$$L(\mathbf{A}) = \frac{1}{2} \sum_{i=1}^n a_i (\mathbf{w}_i - \mathbf{A}\mathbf{v}_i)^2 \quad (8)$$

with the non negative weights a_i submitted to restriction $\sum_{i=1}^n a_i = 1$. The minimization of $L(\mathbf{A})$ can be converted into a maximization problem defining a gain function $g(\mathbf{A})$:

$$g(\mathbf{A}) = 1 - L(\mathbf{A}) = \sum_{i=1}^n a_i \mathbf{w}_i^T \mathbf{A}\mathbf{v}_i \quad (9)$$

Since the attitude matrix \mathbf{A} has nine elements subjects to six independent variables, this optimization problem can be conveniently simplified expressing it in terms of the quaternion $\bar{\mathbf{q}}$, an alternative attitude representation described as a kind of generalization in the three dimensional space of the complex number concept:

$$\bar{\mathbf{q}} = \begin{bmatrix} \mathbf{Q} \\ \mathbf{q} \end{bmatrix} = \begin{bmatrix} \sin(\theta/2)\mathbf{n} \\ \cos(\theta/2) \end{bmatrix} \quad (10)$$

The relationship between the quaternion $\bar{\mathbf{q}}$ and the respective attitude matrix \mathbf{A} is:

$$\mathbf{A}(\bar{\mathbf{q}}) = (\mathbf{q}^2 - \mathbf{Q}\mathbf{Q}^T)\mathbf{I} + 2\mathbf{Q}\mathbf{Q}^T + 2\mathbf{q}\tilde{\mathbf{Q}} \quad (11)$$

Considering

$$\bar{\mathbf{q}}^T \bar{\mathbf{q}} = |\mathbf{Q}|^2 + \mathbf{q}^2 = 1 \quad (12)$$

the gain function $g(\mathbf{A})$ can be written as:

$$g(\bar{\mathbf{q}}) = \bar{\mathbf{q}}^T \mathbf{K} \bar{\mathbf{q}} = \bar{\mathbf{q}}^T \lambda \bar{\mathbf{q}} \quad (13)$$

and the solution of this optimization problem, known as Q-method algorithm, is reduced to a simple generalized problem of eigenvalues and eigenvectors described by (Keat, 1977; Shuster and Oh, 1981)

$$\mathbf{K}\bar{\mathbf{q}}_{opt} = \lambda_{max}\bar{\mathbf{q}}_{opt}, \quad (14)$$

where the optimal quaternion $\bar{\mathbf{q}}_{opt}$ that minimizes the cost function $L(\mathbf{A})$ is the eigenvector associated to maximum eigenvalue λ_{max} of the matrix \mathbf{K} , given by

$$\mathbf{K} = \begin{bmatrix} \mathbf{S} - \sigma\mathbf{I} & \mathbf{Z} \\ \mathbf{Z} & \sigma \end{bmatrix}, \quad (15)$$

where

$$\sigma = \sum_{i=1}^n a_i \mathbf{w}_i \mathbf{v}_i,$$

$$\mathbf{S} = \sum_{i=1}^n a_i (\mathbf{w}_i \mathbf{v}_i^T + \mathbf{v}_i \mathbf{w}_i^T)^T,$$

$$\mathbf{Z} = \sum_{i=1}^n a_i \mathbf{w}_i \times \mathbf{v}_i.$$

7. INTEGRATION POWER SYSTEM/ATTITUDE DETERMINATION

Considering spatial applications, both the power regulation and the attitude estimation must be integrated in an unique, compact and low consumption onboard platform, which must still execute other complementary functions of the satellite such as telemetry, command, control, communication and error analysis. This platform has to acquire the azimuthal position of the sun and the geomagnetic field vectors and to compute the present satellite attitude using Q-method algorithm, as well to read the bus voltage and the battery charge for power control and energy management. Thus, this platform must incorporate sensors, signal conditioners, A/D converters, digital outputs, PWM, processor, memory, parallel and/or serial outputs. In this context, an interesting high performance and low cost option for this application is a DSP platform, which combines a high processing speed processor, great amount of memory and several peripheral devices for real time digital processing signal, such as A/D converters, I/O ports, PWM modules, parallel and serial communication interfaces, and special modules to read encoders, counters, timers, etc. A DSP platform can be programmed using high level language, presenting several tools to develop complex algorithms such as FFT (Fast Fourier Transform), filters and others efficient codes, which allow the substitution of hardware by flexible software in the implementation of indispensable functions for the satellite operation, such as attitude estimation and control, power regulation and management, auto-diagnose, communications, fail analysis, and data storage (Texas Instruments Inc., 2006). The integration of these two important systems for satellite operation using a DSP platform is shown in the Fig.11

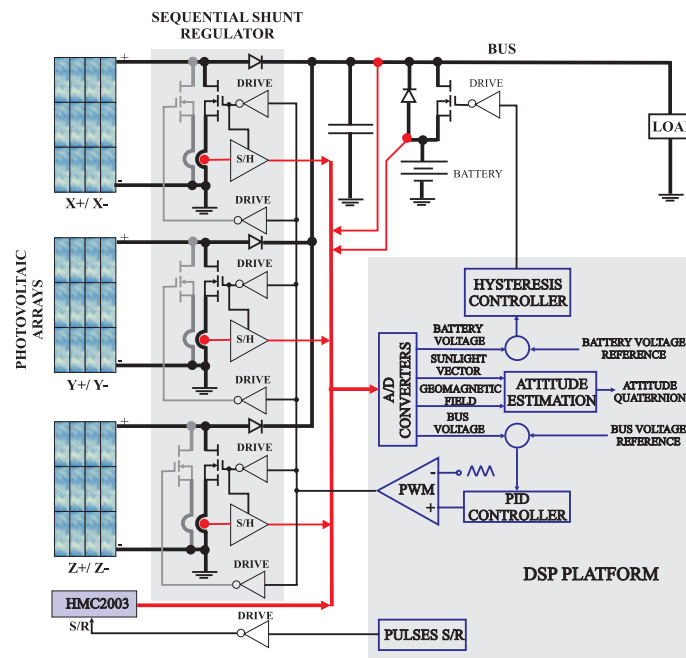


Figure 11. Attitude determination/Power system integration in a DSP platform.

8. EXPERIMENTAL RESULTS

The Q-method algorithm for attitude determination is experimentally implemented using C language in a starter kit module eZdspTMF2808, which is based in the Texas Instruments DSP TMS320F2808. Only two observation vectors w_1 and w_2 are considered in the implementation, which are acquired using sample rate superior to 10 Hz. While a HMC2003 transducer is used to measure the magnetic field produced by Helmholtz coils, the sun sensor is emulated by potentiometers. The vectors v_1 and v_2 are considered fixed and its values are directly inserted in the code. The attitude matrices obtained in the DSP platform and its theoretical values computed in the MATLAB are shown in the table I, where can be observed that this experimental implementation provides a satisfactory attitude estimative with an adequate accuracy for the most of satellite applications.

9. FINAL COMMENTS

Considering a box shape satellite which all sides are covered by photovoltaic arrays, this paper presents a proposal to acquire the azimuthal position of the sun from the own power supply of the artificial satellite. Since the components of the azimuthal position of the sun correspond to the light-generated currents of the each photovoltaic array, they can be evaluated from the operation of the power converter with acceptable accuracy for attitude determination, as observed in the computational simulations. This vector and the geomagnetic field measured by a three-axis magnetic transducer

Table 1. Experimental results

w ₁ and w ₂ are aligned with v ₁ and v ₂										
v ₁	w ₁	v ₂	w ₂	Theoretical attitude matrix			Experimental attitude matrix (DSP)			
0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.9994	0.0352	-0.0006	
1.0000	1.0000	0.0000	0.0000	0.0000	1.0000	0.0000	-0.0352	0.9992	-0.0179	
0.0000	0.0000	1.0000	1.0000	0.0000	0.0000	1.0000	0.0000	0.0179	0.9999	
w ₁ is inclined 45° in relation to v ₁ , while w ₂ and v ₂ are aligned.										
v ₁	w ₁	v ₂	w ₂	Theoretical attitude matrix			Experimental attitude matrix (DSP)			
1.0000	1.0000	0.0000	0.0000	0.7071	-0.7071	0.0000	0.7017	-0.7124	0.0028	
0.0000	1.0000	0.0000	0.0000	0.7071	0.7071	0.0000	0.7124	0.7013	0.0029	
0.0000	0.0000	1.0000	1.0000	0.0000	0.0000	1.0000	-0.0040	0.0000	1.0000	
Reference and observation vectors										
v ₁	w ₁	v ₂	w ₂	Theoretical attitude matrix			Experimental attitude matrix (DSP)			
1.0000	0.7052	0.0000	0.0079	0.7052	-0.0034	0.7090	0.7052	-0.0034	0.7090	
0.0000	0.7088	1.0000	0.0088	0.7089	0.0134	-0.7051	0.7089	0.0134	-0.7051	
0.0000	-0.0135	0.0000	1.0000	-0.0071	0.9999	0.0118	-0.0071	0.9990	0.0118	

are used by a least-square algorithm called Q-method to estimate the attitude of the artificial satellite. This algorithm, which involves a theoretically great computational effort to estimate the satellite attitude, is experimentally implemented in a DSP platform, obtaining satisfactory results for the most of satellite applications. Thus, the integration of two important subsystems for the operation of an artificial satellite can be implemented in this DSP platform, which would realize data acquisition, power regulation, battery management, attitude determination and others important satellites functions. Although a box shape satellite is considered in this work, this proposal can easily adapted for other prismatic configurations. Photovoltaic cells or photodiodes can eventually be used to evaluate the azimuthal position of the sun in satellite configurations where any side is not covered by photovoltaic arrays. An experimental evaluation of the proposed integration between power system and attitude determination will be experimentally implemented in the little prototype of a box-shape satellite shown in Fig. 12, where the subsystems related to power regulation and attitude estimation will be integrated by a DSP platform. Other satellite configuration will be also considered in future studies related to this subject.



Figure 12. Prototype.

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11. Responsibility notice

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