EVALUATION OF SUN POSITION USING THE PHOTOVOLTAIC GENERATION

An Application for Attitude Estimation in Box-Shape Satellites

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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 a 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.

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.). For 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. 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 onboard equipments of an artificial satellite must be pointed to a specified aim to interact with others elements of the spatial system. Thus, the determination of the spatial position and orientation of an artificial satellite, also known as attitude, is fundamental for its perfect operation. The attitude related to an inertial reference is mathematically represented by an operator that rotates a vector inside of a coordinate system, which can be estimated using algorithms that require the observation of at least two independent and known vectors (Shuster and Oh, 1981). 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 which points toward to magnetic north. Since the sun is easily recognized by any object near of the Earth due to its relatively small apparent radius with a high brightness in relation to other astronomical bodies, its azimuthal position related to artificial satellite can be considered as a possible reference vector for attitude determination.

This paper proposes the attitude estimation of an artificial satellite using the own photovoltaic generation to evaluate the azimuthal position of the sun. A mathematical algorithm estimates the satellite attitude using this vector, which is evaluated from the power converter operation, and the Geomagnetic Field, which is measured using a three-axis solid-state magnetometer. 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.

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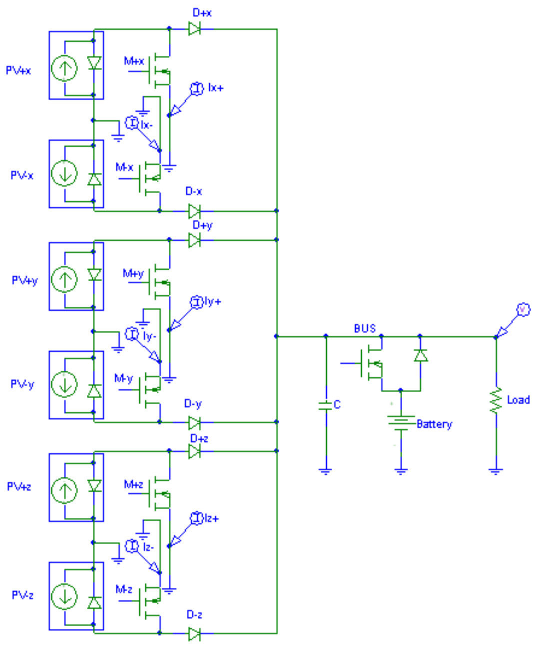

Figure 1: Sequential Shunt Regulator.

2 POWER REGULATION

An artificial satellite generally uses a regulated voltage bus and some form of direct energy transfer for power conditioning of the photovoltaic energy (Shum and Ashley, 1996). Due to a low and relatively constant heat dissipation, the Sequential Shunt Regulator (SSR) is widely used in satellite applications (Garrigós et al., 2006). This power electronic converter is shown in Fig. 1, where is considered a segmented photovoltaic array in six modules. Each photovoltaic module can be admitted as a current source, which contributions are summed by an OR connection of very fast diodes. The photovoltaic current I can either flow to the bus when the MOSFET switch is off, supplying loads and batteries, or be deviated, short-circuiting the photovoltaic module when the MOSFET switch is on. Since the current in the bus is pulsed, a large capacitor filter is required to smooth current pulses and to reduce the voltage ripple.

Since the variations in the capacitor charge reflect the energy exchanges between photovoltaic arrays and electrical loads, the bus voltage must be controlled to assure the power balance, restricting the voltage variations to operational limits 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. The battery operates in stand-by, assuming the load when the bus voltage decreases and the series diode becomes directly polarized, which occurs during eclipses, faults and eventual current peaks. A MOSFET switch can connect the battery to the power bus for its recharge when the satellite is illuminated again.

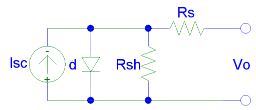

Figure 2: Equivalent electrical circuit of a photovoltaic cell.

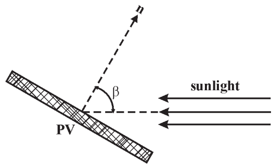

Figure 3: Definition of the sunlight incidence angle β.

3 SUN POSITION ACQUISITION

Usually, the azimuthal position of the sun is evaluated using a sensor based in photovoltaic cells, cameras or CCD sensors (Winetraub et al., 2005; Chen et al., 2006). However, an interesting possibility for artificial satellites is the use of its own photovoltaic system for evaluation of the azimuthal position of the sun (Sityar, 1992; Santoni and Bolotti, 2000; Viscito and Cerise, 2007), since the light-generated power is highly dependent of the intensity and direction of the incident sunlight. A photovoltaic module consists in series-parallel arrays of several photovoltaic cells, which equivalent electrical circuit 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 solar radiation over the photovoltaic cell. This current can be approximated by the mathematical cosine model (Patel, 1999)

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

where the incidence angle β is defined in the Fig. 3. Since the electrical output in the real photovoltaic cells deviates significantly from the proposed cosine model for $\beta > 50^o$, this approach can lead to inaccuracies in the determination of the sun positioning (Winetraub et al., 2005; Sityar, 1992; Patel, 1999). For a better accuracy, it is recommended the use of

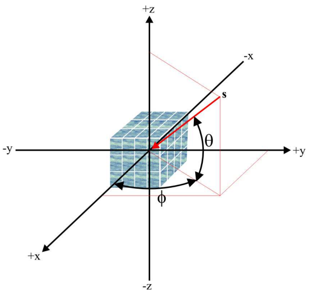

Figure 4: Incidence of the sunlight in a box shaped satellite.

other power-angle curves of the photovoltaic cell, such as the Kelly cosine (Patel, 1999). Neglecting the diode and shunt-leakage currents, which are very small in real cells, the current I_{sc} can be evaluated short-circuiting the output of a photovoltaic array (Sityar, 1992).

An illuminated box shape satellite with all six sides covered by photovoltaic modules is shown in Fig. 4. Considering a coordinate system constituted by the normal axes to the surfaces of this box satellite, a geometric inspection reveals that the components of a vector that points towards to sun are the own summations of light-generated currents of opposite side photovoltaic modules. Thus, the unitary vector $\hat{\mathbf{s}}$ that points towards to sun is given by

$$\hat{\mathbf{s}} = \frac{I_{sc_{+x}} - I_{sc_{-x}}}{I_{sc_x}\big|_{\phi=0^o,\theta=0^o}}\mathbf{i} + \frac{I_{sc_{+y}} - I_{sc_{-y}}}{I_{sc_y}\big|_{\phi=90^o,\theta=0^o}}\mathbf{j} + \frac{I_{sc_{+z}} - I_{sc_{-z}}}{I_{sc_z}\big|_{\theta=90^o}}\mathbf{k}, \quad (2)$$

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 $-z$.

The scheme for acquisition of azimuthal position of the sun from the SSR operation is shown in Fig. 5. When the outputs of opposite photovoltaic module are short-circuited by their respective shunt MOSFET's of the power converter, a Hall current transducer measures the differential light-generated current in the respective coordinate axis. This signal is sampled in S/H circuit while the shunt MOSFET's are on. When the shunt MOSFET's are off, the S/H circuit holds the differential current measurement, assuring that this component of vector $\hat{\mathbf{s}}$ is always availed for acquisition.

4 SIMULATION RESULTS

The acquisition of the vector sun position is verified from a computational simulation of the SSR using the SimPowerSystems of the MATLAB/SIMULINK. It is

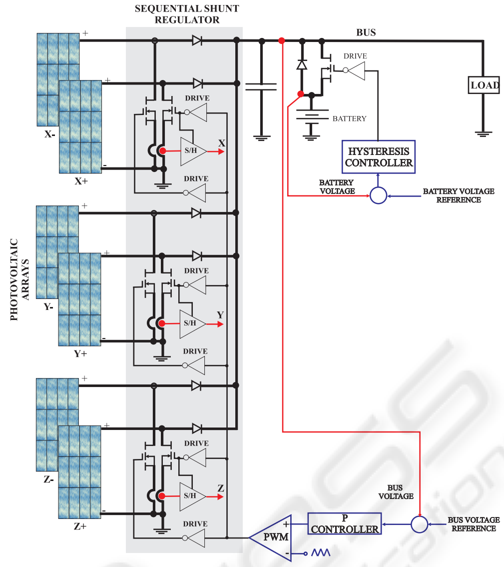

Figure 5: Scheme for acquisition of azimuthal position of the sun from the SSR and bus voltage regulation.

considered that a box shape satellite is rotating in the space at $\dot{\phi} = 1.26$rad/s and $\dot{\theta} = 6.28$rad/s (see Fig. 4). The surface of this satellite is covered by six photovoltaic arrays that generates $6 \times 10W_p$ at an irradiance of $1000W/m^2$. 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. Since the bus capacitance behaves as a big integrator, a simple proportional controller, which gain is adjusted to 300, is enough for a null error in the regulation of the bus voltage. The voltage reference is adjusted to 15V to supply a resistive load of 90Ω and a 12V battery. A hysteresis controller monitors the battery charge and commands the MOSFET switch, connecting 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.

The real and acquired azimuthal sun position is shown in the Fig. 6. The error in the acquired vector is small, basically caused by the sample operation. 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. 7.

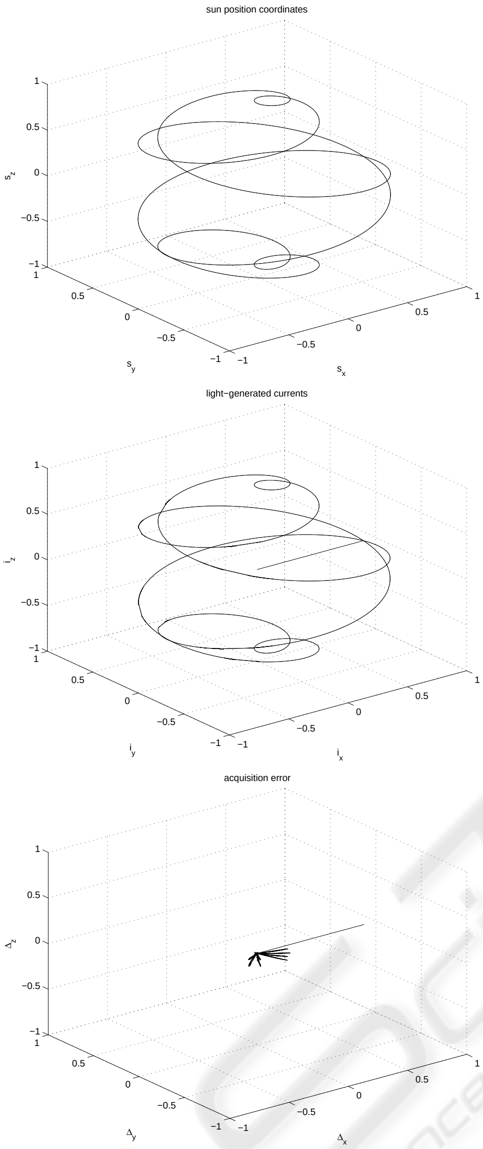

Figure 6: Azimuthal position of the sun.

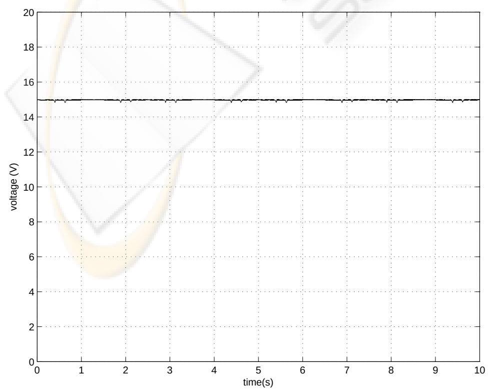

Figure 7: Regulated bus voltage in the Sequential Shunt Regulator.

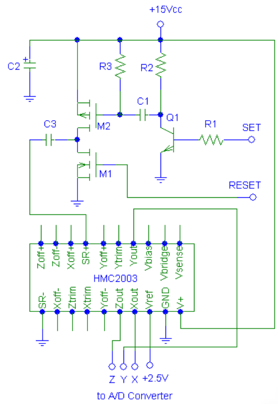

Figure 8: Magnetometer circuit.

5 MAGNETOMETER CIRCUIT

The measurement circuit for Geomagnetic Field is shown in Fig. 8. The heart of this circuit is a small solid-state three-axis magneto-resistive transducer Honeywell HMC2003,which output voltage signals are proportional to the magnitudes of the three ordinal components of the applied magnetic field in a range of the 0 to +5V, where +2.5V represents the reference value for a null intensity of the magnetic field. In order to maximize the transducer resolution, a strong SET/RESET pulse must be occasionally applied to transducer to eliminate the effect of the past magnetic history and to avoid the degradation of the output signal. The output voltage signals X, Y and Z can be connected directly to an analog-to-digital (A/D) converter.

6 ATTITUDE ESTIMATION

A common way to specify the attitude of a body is the use of the Euler's angles $\psi\theta\phi$, which 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. Considering a stipulated reference vector $\mathbf{v}_i$, its rotation to obtain an observed vector $\mathbf{w}_i$ by one of the n sensors of the satellite is described as

$$\mathbf{w}_i = \mathbf{A}\mathbf{v}_i, \tag{3}$$

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

$$L(\mathbf{A}) = \frac{1}{2}\sum_{i=1}^{n} a_i(\mathbf{w}_i - \mathbf{A}\mathbf{v}_i)^2 \tag{4}$$

with the non negative weights a_i submitted to restriction $\sum_{i=1}^{n} a_i = 1$ (Shuster and Oh, 1981). This optimization problem can be conveniently simplified expressing it in terms of the quaternion $\bar{\mathbf{q}}$, an alternative attitude representation defined as:

$$\bar{\mathbf{q}} = \begin{bmatrix} \mathbf{Q} \\ \mathbf{q} \end{bmatrix} = \begin{bmatrix} \sin(\theta/2)\mathbf{n} \\ \cos(\theta/2) \end{bmatrix} \quad (5)$$

and related with an attitude matrix $\mathbf{A}$ by:

$$\mathbf{A}(\bar{\mathbf{q}}) = (\mathbf{q}^2 - \mathbf{Q}\mathbf{Q}^T)\mathbf{I} + 2\mathbf{Q}\mathbf{Q}^T + 2\mathbf{q}\tilde{\mathbf{Q}} \quad (6)$$

In terms of quaternions, the solution of this optimization problem is given by an algorithm known as Q-method, which consists of a simple generalized problem of eigenvalues and eigenvectors described by (Keat, 1977; Shuster and Oh, 1981)

$$\mathbf{K}\bar{\mathbf{q}}_{opt} = \lambda_{max}\bar{\mathbf{q}}_{opt}, \quad (7)$$

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

$$\mathbf{K} = \begin{bmatrix} \mathbf{S} - \sigma\mathbf{I} & \mathbf{Z} \\ \mathbf{Z} & \sigma \end{bmatrix}, \quad (8)$$

where $\sigma = \sum_{i=1}^{n} a_i \mathbf{w}_i \mathbf{v}_i$, $\mathbf{S} = \sum_{i=1}^{n} a_i (\mathbf{w}_i \mathbf{v}_i^T + \mathbf{v}_i \mathbf{w}_i)^T$, and $\mathbf{Z} = \sum_{i=1}^{n} a_i \mathbf{w}_i \times \mathbf{v}_i$.

7 INTEGRATION

Considering spatial applications, both the power regulation and the attitude estimation must be integrated in an unique, compact and low consumption onboard platform, which should read analog signals, compute the present satellite attitude, and perform the power control and energy management. This platform must still execute other complementary functions of the satellite such as telemetry, command, control, communication and error analysis. In this context, an interesting high performance and low cost option is a DSP-based 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. The programming uses high level language, presenting several tools to develop complex algorithms such as FFT (Fast Fourier Transform), filters and other indispensable functions for the satellite operation, such as attitude estimation and control, power regulation and management, auto-diagnose, communications, fail analysis, and data storage.

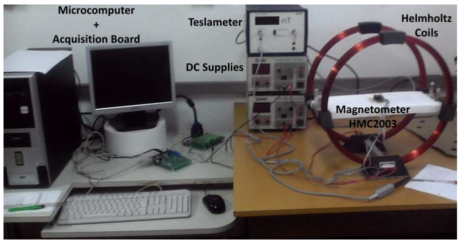

Figure 9: Experimental implementation.

8 EXPERIMENTAL RESULTS

The Q-method algorithm is experimentally implemented using C language in a starter kit module based in the Texas Instruments DSP TMS320F2808. A photography of this practical implementation is presented in the Fig. 9. While reference vectors $\mathbf{v}_1$ and $\mathbf{v}_2$ are considered fixed and its values are directly inserted in the code, the observation vectors $\mathbf{w}_1$ and $\mathbf{w}_2$ are acquired using sample rate superior to 10 Hz. The vector $\mathbf{w}_1$ is the magnetic field produced by Helmholtz coils, which is measured using the magnetometer circuit presented in Fig 8, while the vector $\mathbf{w}_2$ is emulated by potentiometers. The experimental results of implementation considering two static known situations are shown in the table I, where is observed that this DSP platform can provide satisfactory attitude estimations for this satellite application.

9 FINAL DISCUSSION

This paper presents a proposal to acquire the azimuthal position of the sun using the own power photovoltaic supply of an artificial satellite. Considering a box shape satellite, where all sides are covered by photovoltaic modules, the components of the azimuthal position of the sun correspond to summations of the light-generated currents by opposite photovoltaic modules, which can be evaluated from the operation of the SSR power converter. In the eventual absence of a photovoltaic module, photovoltaic cells or photodiodes can substitute it in the satellite configuration. This information about the sun position and the measurement of other known vector, such as the Geomagnetic Field, can be used to estimate the attitude, allowing the integration of two of the more important subsystems for the operation of an artificial satellite. The integration of these subsystems can be implemented in a DSP platform, which would realize data acquisition, power regulation, battery management, attitude determination and others important satellites functions. The simulation results

Table 1: Experimental results.

$\mathbf{w}_1$ and $\mathbf{w}_2$ are aligned with $\mathbf{v}_1$ and $\mathbf{v}_2$.

	$\mathbf{v}_1$	$\mathbf{w}_1$	$\mathbf{v}_2$	$\mathbf{w}_2$
x	0.0000	0.0000	0.0000	0.0000
y	1.0000	1.0000	0.0000	0.0000
z	0.0000	0.0000	1.0000	1.0000

Theoretical attitude matrix

$$\begin{bmatrix} 1.0000 & 0.0000 & 0.0000 \\ 0.0000 & 1.0000 & 0.0000 \\ 0.0000 & 0.0000 & 1.0000 \end{bmatrix}$$

Experimental attitude matrix (DSP)

$$\begin{bmatrix} 0.9994 & 0.0352 & -0.0006 \\ -0.0352 & 0.9992 & -0.0179 \\ 0.0000 & 0.0179 & 0.9999 \end{bmatrix}$$

$\mathbf{w}_1$ is inclined 45^o in relation to $\mathbf{v}_1$, while $\mathbf{w}_2$ and $\mathbf{v}_2$ are aligned.

	$\mathbf{v}_1$	$\mathbf{w}_1$	$\mathbf{v}_2$	$\mathbf{w}_2$
x	1.0000	1.0000	0.0000	0.0000
y	0.0000	1.0000	0.0000	0.0000
z	0.0000	0.0000	1.0000	1.0000

Theoretical attitude matrix

$$\begin{bmatrix} 0.7071 & -0.7071 & 0.0000 \\ 0.7071 & 0.7071 & 0.0000 \\ 0.0000 & 0.0000 & 1.0000 \end{bmatrix}$$

Experimental attitude matrix (DSP)

$$\begin{bmatrix} 0.7017 & -0.7124 & 0.0028 \\ 0.7124 & 0.7013 & 0.0029 \\ -0.0040 & 0.0000 & 1.0000 \end{bmatrix}$$

Reference and observation vectors

	$\mathbf{v}_1$	$\mathbf{w}_1$	$\mathbf{v}_2$	$\mathbf{w}_2$
x	1.0000	0.70523	0.0000	-0.00793
y	0.0000	0.70884	1.0000	0.00881
z	0.0000	-0.01353	0.0000	0.99999

Theoretical attitude matrix (MATLAB)

$$\begin{bmatrix} 0.70522 & -0.00338 & 0.70897 \\ 0.70894 & 0.01337 & -0.70513 \\ -0.00709 & 0.99990 & 0.01183 \end{bmatrix}$$

Experimental attitude matrix (DSP)

$$\begin{bmatrix} 0.70523 & -0.00337 & 0.70896 \\ 0.70894 & 0.01339 & -0.70513 \\ -0.00711 & 0.99904 & 0.01183 \end{bmatrix}$$

shows that the azimuthal position of the sun can be evaluated from the SSR operation with sufficient accuracy for attitude determination. The results of the experimental implementation in a DSP platform of the q-Method, an algorithm that involves a theoretically great computational effort, are satisfactory for this satellite application. An experimental evaluation of this proposal will realized using the little prototype of a box-shape satellite (Fig. 10), 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 10: Box-shape structure.

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