SYNERGY IN POWER AND MOMENTUM MANAGEMENT FOR SPACECRAFT USING DOUBLE GIMBALED SOLAR ARRAYS

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Abstract: A system design concept is presented for the unloading of wheel momentum with double gimbaled solar arrays on satellites, where momentum control and optimal power generation are combined. The unloading makes use of the gravity gradient torque. The dynamic equations of the external torques and the satellite dynamics are derived to establish a system model. An optimal controller is designed and an overall analytic model is established for fast system solution. Several system design parameters are identified during the model definition. Feasibility of the concept will be demonstrated by closed-loop optimization of the established system design parameters. High power generation capability will be demonstrated with simultaneous momentum management.

Keywords: satellite control, spacecraft autonomy, optimal control, angular momentum, energy management systems, gimbals, analytic approximations, system analysis, system models

1. INTRODUCTION

In the near future, smaller and more cost efficient satellites could become an important factor in space applications due to comparably less development and launch costs as well as recent advances in micro- and nano-technology. These so called nano-satellites with a total weight of about 10 kg require new concepts for the overall system design. One important part of this concept will be the transition from the traditional subsystem structure to multifunctional structures, where equipment or parts of equipment perform more than one function at the same time.

The article presents a concept for the system design of nano-satellites with bias-momentum wheels for attitude control, where synergy is generated by combining momentum unloading with an optimized power generation scheme based on a double gimbaled solar array assembly as shown in Fig. 1.

The solar arrays on standard earth oriented satellites are rotated to the sun by a single axis mechanism allowing for sun tracking in the orbit plane. Due to the ecliptic, even for equatorial orbits the full capability of power generation is not realized with a single axis mechanism. Especially for orbits with higher inclination, the efficiency of solar arrays with single axis mechanisms is significantly reduced. For these orbits either a dual axis mechanism has to be introduced or the size of the solar arrays has to be increased to generate the required power.

By using a dual axis mechanism for solar array rotation, not only the power efficiency of a solar array can be increased, but it is also possible to exploit the resulting gravity gradient torques to unload the momentum wheels, used for attitude control. The proposed solution can be combined with any other standard momentum unloading scheme (thrusters, magnetic torquers) to increase the satellite redundancy or operational capabilities.

The well known disadvantage of a dual axis mechanism (complexity, cost, and reliability) for larger satellites can be overcome for nano-satellites by using adaptive structures to realize the second angle rotation. Some realization variants of the dual axis

mechanism by adaptive technologies already available today are shown in (auf der Heide and Janschek, 2001).
The main scope of the article is directed towards new aspects of a system design and optimization for a solar array with a dual axis mechanism for power generation and momentum control. The governing dynamic models and external disturbances for the configuration are presented and an analytical solution is derived. A closed loop control scheme is developed and implemented to control the solar array motion. For the resulting closed-loop system an analytical solution is derived, which enables the user to perform parameter studies and optimization with the closed-loop system. Key system design parameters (e.g. orbit parameters and satellite configuration) will be identified and closed-loop optimization results are shown for low-earth orbits, which demonstrate the feasibility of the concept.

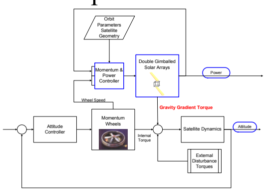

Fig. 1. Block diagram of combined momentum and power management systems.

2. PRINCIPAL FUNCTION & REALIZATION

A double gimbaled solar array concept is proposed where the gravity gradient is exploited to unload the wheel momentum by solar array steering. Synergy is created by simultaneously maximizing the power generation. It is assumed that momentum wheels are available for attitude control. As these wheels can only exert internal torques, a bias on the external torque environment will lead to increased momentum on the wheels enforcing an unloading action.
An event based control principle is applied such that the solar arrays nominally follow exactly the sun to generate power. In the eclipse phases of the satellite it is not necessary to point the solar arrays to the sun. During these phases the momentum unloading controller will be activated. The tracking of the sun outside the ecliptic is performed as long as a predefined momentum level on the wheels is not exceeded. If this predefined momentum level is reached the control function will be activated. The controller then unloads the wheel momentum in minimum time. It is evident that during the sun tracking operations unwanted gravity gradient torques are generated. Therefore, an additional controller will be implemented that allows for slight defocusing of the solar arrays outside the ecliptic in favor of momentum accumulation. The controller design will be demonstrated in paragraph 4. In the following paragraph the dynamic model of the satellite and the environment will be derived.
The concept incorporates a dual axis mechanism for the solar array orientation. The known disadvantages of such mechanisms for larger satellites such as complexity, cost, and reliability can be overcome for small satellites by using adaptive structures to realize the second angle rotation. Even existing adaptive technologies such as piezoelectric or magnetostrictive effects can be used in inch-worm motors as discussed in (auf der Heide and Janschek, 2001).

3. MODEL DERIVATION

In this paragraph relevant principles on the derivation of the simulation model will be presented. The dependence of the external torques on the sun motion due to the double gimbaled solar arrays will be described. All external torques such as aerodynamic, gravity gradient, magnetic, and solar pressure shall be modeled. First the motion of the sun and the mechanism kinematics will be defined which is necessary to proceed with the derivation of the torque models.

3.1. Sun Motion

The motion of the sun in a local vertical and horizontal reference frame (x or roll axis in direction of flight, z axis or yaw nadir pointing) can be described as follows by Equ. (1). The time dependent elements are sorted and separated to facilitate further simplification:

$$\mathbf{s}_{LVLH} = \begin{pmatrix} s_x \\ s_y \\ s_z \end{pmatrix} = \begin{pmatrix} -\cos\Omega & \cdot\sin(nt) & \cdot\cos(n_s t) \\ -\sin\Omega\cos\varepsilon & \cdot\sin(nt) & \cdot\sin(n_s t) \\ -\sin\Omega\cos i & \cdot\cos(nt) & \cdot\cos(n_s t) \\ +\cos\Omega\cos i\cos\varepsilon & \cdot\cos(nt) & \cdot\sin(n_s t) \\ +\sin i\sin\varepsilon & \cdot\cos(nt) & \cdot\sin(n_s t) \\ & & \\ -\sin\Omega\sin i & & \cdot\cos(n_s t) \\ +\cos\Omega\cos\varepsilon\sin i & & \cdot\sin(n_s t) \\ -\sin\varepsilon\cos i & & \cdot\sin(n_s t) \\ & & \\ -\cos\Omega & \cdot\cos(nt) & \cdot\cos(n_s t) \\ -\sin\Omega\cos\varepsilon & \cdot\cos(nt) & \cdot\sin(n_s t) \\ +\sin\Omega\cos i & \cdot\sin(nt) & \cdot\cos(n_s t) \\ -\cos\Omega\cos i\cos\varepsilon & \cdot\sin(nt) & \cdot\sin(n_s t) \\ -\sin i\sin\varepsilon & \cdot\sin(nt) & \cdot\sin(n_s t) \end{pmatrix} \quad (1)$$

The sun motion depends on the orbit parameters such as right ascension Ω, inclination i, the ecliptic angle ε, and the orbit frequency n and the frequency of the earth rotation around the sun n_S. This description of the sun motion can be further simplified by reducing the description of the in plane motion along the roll and yaw axis of the sun to a sum of two different periodical motions:

$$\mathbf{s}_{LVLH} = \begin{pmatrix} A_1^x \sin((n+n_s)t+\varphi_1^x) + A_2^x \sin((n-n_s)t+\varphi_2^x) \\ A_1^y \sin(n_s t+\varphi_1^y) \\ A_1^z \sin((n+n_s)t+\varphi_1^z) + A_2^z \sin((n-n_s)t+\varphi_2^z) \end{pmatrix} \quad (2)$$

This simplification can be done by simple trigonometric operations. The definition for the resulting amplitudes A and phases φ can be found in (Tkocz, 2003).

3.2. Solar Array Gimbals

A double gimbaled solar array is proposed where two arrays are located perpendicular to the orbit plane (see Fig. 2). In a local vertical and horizontal coordinate system the rotation angles are realized first around the pitch axis and consequently around a local roll axis.
The following equation gives the relation between the normal vector to the sun s and the orientation angles of the array. The nominal orientation of the solar array is pointing to the zenith:

$$\begin{pmatrix} \cos p & 0 & -\sin p \\ \sin p \sin r & \cos r & \cos p \sin r \\ \sin p \cos r & -\sin r & \cos p \cos r \end{pmatrix} \cdot \begin{pmatrix} s_x \\ s_y \\ s_z \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ -1 \end{pmatrix} \tag{3}$$

The solar array rotation around the pitch axis is equal to the orbit frequency subtracted by the frequency of rotation of the earth around the sun. The array rotation about the roll axis has the frequency of a year due to the out of orbit plane motion of the sun.

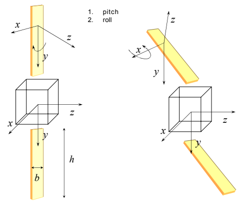

Fig. 2. Double Gimbaled Solar Array Configuration.

A limited number of cases for the orientation of the solar array exist as already stated in paragraph 2:

1. power generation
   the solar array is pointing to the sun $n = s$
2. momentum control
   the solar array has a periodically constant orientation $n = n_{ctr}$
3. power generation and momentum control
   the solar array follows the sun with some limitation $n = s_{red}$

During the normal operation the solar array will be pointing exactly to the sun as defined in eq. (1). During momentum management phases the solar array orientation will be constant for a limited time (see paragraph 4). Furthermore, momentum management and power generation can be combined by some reduction of the exact pointing angles. The details will be described in paragraph 4.

3.3. *Momentum Model*

It is assumed that the satellite attitude is controlled by momentum wheels. The attitude and momentum dynamics are defined with the principle of momentum conservation. As the dynamics are separated by their time constants the description of the satellite dynamics for our purpose may be reduced to the momentum dynamics as in (auf der Heide, 2004):

$$\begin{aligned} I_x \cdot \dot{\omega}_x - n \cdot I_z \cdot \omega_z &= T_x \\ I_y \cdot \dot{\omega}_y &= T_y \\ I_z \cdot \dot{\omega}_z + n \cdot I_x \cdot \omega_x &= T_z \end{aligned} \tag{4}$$

The equation relates the wheel inertia I and speed ω with the external torques T. For perfect attitude control the wheels directly compensate the external torques. The momentum equation is coupled in the roll and yaw axis. Investigations performed in (auf der Heide, 2004) show that the dominant part with respect to momentum dynamics is the roll/yaw system. Equ. (4) is linear and can be solved by Laplace transformation depending on the definition of the external torques.

$$\begin{pmatrix} \omega_x \\ \omega_z \end{pmatrix} = \begin{pmatrix} \cos nt & n \cdot \frac{I_z}{I_x} \cdot \sin nt \\ -n \cdot \frac{I_x}{I_z} \cdot \sin nt & \cos nt \end{pmatrix} \cdot \begin{pmatrix} \omega_x^0 \\ \omega_z^0 \end{pmatrix} +$$
$$L^{-1}\left\{ \begin{pmatrix} \frac{s}{s^2+n^2} & \frac{I_z}{I_x} \cdot \frac{n}{s^2+n^2} \\ -\frac{I_x}{I_z} \cdot \frac{n}{s^2+n^2} & \frac{s}{s^2+n^2} \end{pmatrix} \cdot \begin{pmatrix} \frac{1}{I_x} \cdot L\{T_x\} \\ \frac{1}{I_z} \cdot L\{T_z\} \end{pmatrix} \right\} \tag{5}$$

To enable a solution by Laplace transformation it is necessary to define the external torques as linear superposition of constant and harmonic elements:

$$\mathbf{T} = \begin{pmatrix} \sum_i C_{Ti}^x + \sum_i A_{nTi}^x \sin(nt + \varphi_{nTi}^x) + \sum_i A_{Ti}^x \sin(\omega_{Ti}^x t + \varphi_{Ti}^x) \\ \sum_j C_{Tj}^y + \sum_j A_{nTj}^y \sin(nt + \varphi_{nTj}^y) + \sum_j A_{Tj}^y \sin(\omega_{Tj}^y t + \varphi_{Tj}^y) \\ \sum_k C_{Tk}^z + \sum_k A_{nTk}^z \sin(nt + \varphi_{nTk}^z) + \sum_k A_{Tk}^z \sin(\omega_{Tk}^z t + \varphi_{Tk}^z) \end{pmatrix} \tag{6}$$

The derivation of the torques in the following paragraph shall be performed accordingly.

3.4. *Description of Torques*

All external disturbance torques have been modeled. Nevertheless, the gravity gradient torque and the magnetic torque are dominant for the orbits that are deemed relevant for the combined momentum management and power generation. The solar pressure torque has also some influence while the aerodynamic torque can be in principal neglected for higher orbit altitudes.

The Gravity Gradient Torque depends on the orientation of the solar arrays as published in (auf der Heide and Janschek, 2002):

$$\begin{aligned} T_{GG}^X &= n^2 \cdot \cos p \cdot \sin 2r \cdot m_{sa} \cdot h^2 \\ T_{GG}^Y &= \frac{1}{2} \cdot n^2 \cdot \left(m_{sa} \cdot h^2 \cdot (\cos 2r - 1) + \frac{1}{2} \cdot m_{sa} \cdot b^2 \right) \cdot \sin 2p \end{aligned} \tag{7}$$

Here, m_{sa} is the mass of one solar array, h is the length of the array along the pitch axis (height) and b is the extension perpendicular to that; the product of b and h is defining the area of one solar array. p and r are the pitch and roll angle of the solar array. The troque can also be defined with respect to the components of the sun vector s:

$$\mathbf{T}_G = -2n^2 m_{sa} \begin{pmatrix} s_z s_y h^2 \\ h^2 \frac{{s_y}^2 s_x s_z}{1 - {s_y}^2} - \frac{1}{4} b^2 \frac{s_x s_z}{1 - {s_y}^2} \\ 0 \end{pmatrix} \tag{8}$$

Using the simplified model for the sun vector from equation (2), the description of the gravity gradient torque can be written in a form according to equation (6) by making use of an adequate simplification of the denominator $1 - {s_y}^2$.

The detailed transformation of Equ. (8) into the form of Equ. (6) will not be performed here due to limited space available, but can be found in (Tkocz, 2003) for both constant solar array pointing and sun tracking.

The gravity gradient torque in the dominant roll/yaw system is depending on the height h of the solar array only. By varying h together with b the power (area of the solar array) can be kept constant while the torque environment is influenced. h is a key system design parameter.

The Magnetic Torque is independent of the solar array position. The description of the magnetic torque in a first order model is given in (auf der Heide and Janschek, 2002) and it is only depending on the orbit frequency. A description according to equation (6) can easily be established:

$$\mathbf{T}_M = -\frac{R^3}{r^3} B_0 \begin{pmatrix} 2m_y \sin i \sin nt + m_z \cos i \\ \sqrt{{m_z}^2 + 4{m_x}^2} \sin i \sin\left(nt + \arctan \frac{m_z}{-2m_x} \right) \\ -m_y \sin i \cos nt - m_x \cos i \end{pmatrix} \tag{9}$$

Here R is the earth radius, r is the orbit radius, m is the residual magnetic moment of the satellite i is the inclination of the orbit, and n is the orbit frequency.
The satellite residual magnetic moment $m = (m_x, m_y, m_z)^T$ determines the magnetic torque. Therefore, this parameter is also identified as a key system design parameter.

The Solar Pressure Torque is strongly depending on the solar array orientation:

$$\mathbf{T}_S = |\mathbf{s} \cdot n_{sa}| \cdot A \cdot p_S \cdot [-\Delta_{cog} \times (-\mathbf{s})] \qquad (10)$$

In this equation s represents the sun vector, n_{sa} the normal vector on the solar array, A the area of the solar array, p_s the solar pressure constant, and Δ_{cog} the offset between geometrical center and center of gravity.
The transformation of (10) by use of trigonometric relations to the simplified form of (6) is shown in (Tkocz, 2003) and will not be exercised here.

The Aerodynamic Torque is dominating only for orbit altitudes below 600 km. Nevertheless, it has been modeled in the system environment. The general form is similar to equation (10):

$$\mathbf{T}_A = |\mathbf{v} \cdot n_{sa}| \cdot A \cdot p_A \cdot [\Delta_{\mathbf{cog}} \times (-\mathbf{v})] \qquad (11)$$

Here, v is the velocity of the satellite.

4. CONTROLLER DESIGN

An event based controller is proposed to combine power generation with momentum management, which may make use of different mission phases of the satellite to prioritize either power generation or momentum management. As already defined above some environmental conditions can be directly exploited: during eclipse phases of the satellite the solar arrays may be used for momentum unloading. Other mission criteria can be added easily.
Outside eclipse the power generation shall be prioritized as long as the wheel momentum does not exceed a predefined level. Whenever this level is exceeded a momentum unloading will be performed.
For momentum unloading one controller is used independent of mission phase. The momentum unloading is performed in a time optimal manner. The open-loop controller design for the linear plant can be performed as demonstrated in Föllinger (1994) and shown in (auf der Heide and Janschek, 2001) and (auf der Heide and Janschek, 2002).
The plant is linear according to equation (4). Because the gravity gradient torque is used as control input, a control input can only be established for the roll and pitch axis. As the roll/yaw system is coupled these inputs are sufficient to make the system controllable. The Equ. (4) shall be simplified by using unit inertia for the wheels and defining a control input u, which is in principle defined in Equ. (7):

$$\begin{pmatrix} \dot{\omega}_x \\ \dot{\omega}_y \\ \dot{\omega}_z \end{pmatrix} = \begin{pmatrix} 0 & 0 & -n \\ 0 & 0 & 0 \\ n & 0 & 0 \end{pmatrix} \cdot \begin{pmatrix} \omega_x \\ \omega_y \\ \omega_z \end{pmatrix} + \begin{pmatrix} 1 & 0 \\ 0 & 1 \\ 0 & 0 \end{pmatrix} \cdot u \qquad (12)$$

The optimization criterion weights how to bring the system from one state into the other in minimum time;

$$J = \int_0^{t_e} 1\, dt = t_e \qquad (13)$$

The boundary conditions for the problem are:

$$x(0) = x_0 \ , \ x(t_e) = 0 \qquad (14)$$

The control input is limited, where the limit M depends on the solar array angles:

$$|u| \le M \qquad (15)$$

The resulting controller is the well-known bang-bang controller, which can be derived by simply applying Lyapunov's minimum principle. During control phases the solar array will be constantly pointing in two min/max directions which create the maximum gravity gradient torque according to the resulting control law:

$$u = \begin{pmatrix} -M \cdot sign(\omega_x) \\ -M \cdot sign(\omega_y) \\ 0 \end{pmatrix} \qquad (16)$$

Here, M is the maximum amplitude of the gravity gradient torque depending on the angles of the solar array (see Equ.(7)), ω is the wheel speed of the momentum wheels.
The complete solution depends on a nonlinear matrix exponential integral equation, which even in simple cases is hard to solve analytically. Therefore, the solution for the second order roll/yaw system is established by construction of system trajectories as demonstrated in Föllinger (1994).
The system trajectories of the controlled system are circles according to the integration of the roll/yaw dynamics in (4). The center of the circular trajectories is in M, the magnitude of the control input:

$$u+ = -M : (\omega_z - M/n)^2 + \omega_x = C$$
$$u- = -M : (\omega_z + M/n)^2 + \omega_x = C \qquad (17)$$

To drive the system from one momentum state to another the control input will be switched according to Equ. (16). For the roll/yaw system the optimal trajectory is shown in Fig. 3 from one initial state where the wheel speed ω_z has some initial value and ω_x is zero. The controlled trajectories are circles as defined in Equ. (17). The control input sign is switched with the sign of the wheel speed in the roll axis ω_x.
It can be shown that for the purpose of controlling the system the control law (Equ. (16)) can be chosen independently from the initial states. This is especially true when the controller is switched off before completely reducing the momentum to zero. This also helps to avoid chattering of this bang-bang type controller. The complete derivation of the controller and stability is shown in (auf der Heide, 2004).
The solution for the first order pitch system can be found by solving the equations analytically, leading to the control law already stated in Equ. (16).

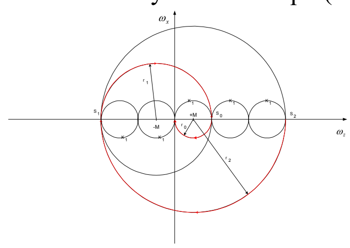

Fig. 3. Optimal roll/yaw trajectory for bang-bang control.

In addition to the time optimal controller for momentum unloading it can be observed that sun tracking creates unwanted gravity gradient torques, which lead to unwanted momentum on the wheels. Therefore, an additional controller is implemented which performs a so called reduced sun tracking. Here, the local roll angle of the solar array, which is responsible for the major momentum load, is reduced. This reduced pointing can be expressed in one parameter, which relates to the sun vector as follows:

$$n_{s.a.} = \begin{pmatrix} s_x \\ \alpha \cdot s_y \\ s_z \end{pmatrix} \tag{18}$$

This parameter shall be taken as a key system design parameter. A trade-off can be performed by reducing power generation such that the momentum unloading during the sun phases is minimized leading to an overall increase in the mean generated power over one year.

5. SYSTEM OPTIMIZATION RESULTS

This paragraph shows the optimization results of the proposed solar array mechanism for combined momentum and power management.

The satellite configuration is as shown in Fig. 2. The mass of the satellite body is 7 kg, the mass of one array is 2.4 kg. The area of each array is constant with $2m^2$ leading to a power generation of approx. 400 W. The moments of inertia are approx. 1 kgm^2.

The results are presented for several design parameters which shall be summarized for better overview:

- Orbit parameters:
  Results are shown for different orbit parameters such as orbit radius, inclination, and right ascension. The results will be limited to LEO to MEO where the gravity gradient torque dominates.
- Satellite design parameters:
  Key satellite design parameters have been identified such as the residual magnetic flux *m* and the solar array geometry represented by its height *h*. All results that will be presented are optimized with respect to these two design parameters.
- Controller Parameters:
  One key design parameter is defined for the controller which allows for reduced sun tracking with respect to the local roll angle of the array. This parameter has been optimized.

All results given in the following figures show the mean generated power while momentum is limited to a predefined value (0.4 Nms). The mean power is computed at least for one year in orbit to account for the seasonal influence. The mean power is given in percent, where 100% is reached by ideal sun tracking. The following Fig. 4 shows the optimization results for orbit altitudes of 1.000, 5.000, 10.000, and 15.000 km. All results are shown for inclinations between 0 and 180°. For each orbit altitude three angles of the right ascension *R.A.* are also evaluated which are 0, 45, and 90°.

For orbit altitudes between 1.000 and 10.000 km the mean power that is generated over one year is never below 90% of the maximum power that can be generated. This means that for momentum control approximately 10% of the maximum generable power has to be sacrificed. Each of the presented optimization results has a certain optimal value for magnetic flux, solar array geometry, and roll angle reduction.

For orbits of 15.000 km the efficiency of the proposed mechanism already decreases, but depending on the orbit parameters the proposed mechanism may still be useful.

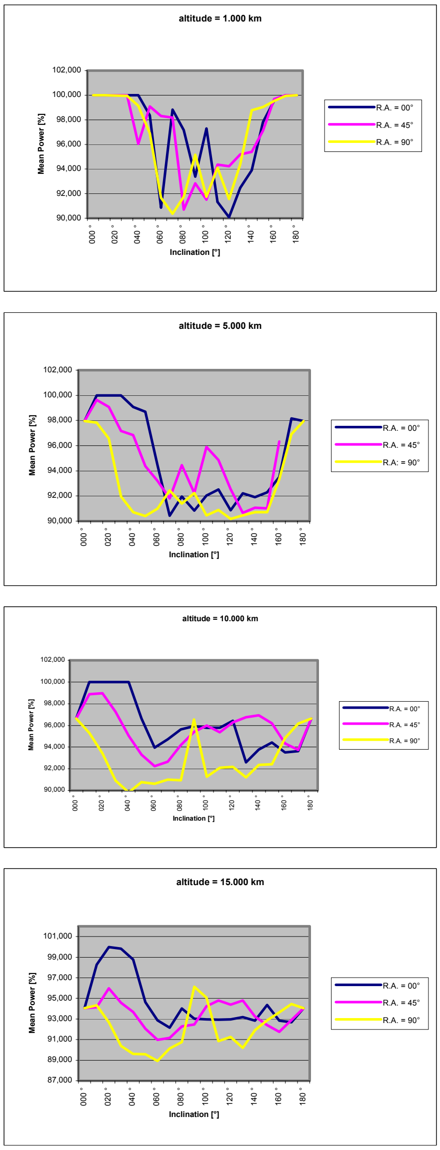

Fig. 4. Optimization results for optimal power and simultaneous momentum management for different parameters.

For the optimized parameters it can be in general observed that the higher the orbit the taller ($h > b$, variation range between h 0.8 … 2.6 m) the solar arrays will be. The residual magnetic flux rather depends on the orbit inclination and is more or less independent of the orbit altitudes considered (between -.1 … +.2 Am^2). The roll angle reduction is also used for all orbits, but rather extensive for higher orbits (variation between 0 … 1). The smaller the angle to the ecliptic the larger this roll angle reduction may be, where the effect in these cases is limited.

The Fig. 5 shows the optimization results compared to a single axis mechanism. The single axis mechanism produces full power when the orbit has no angle to the ecliptic; then no roll angle is necessary. The single axis mechanism has reduced power generation capability the larger the elevation angle of the sun will be with the orbit plane. Especially for high elevation angles of the sun with respect to the orbit plane the dual axis mechanisms power generation capability is considerably higher.

For an orbit altitude of 10.000 km the additional controller which reduces the local roll angle for sun tracking has been turned off and the results have been compared to the results with roll angle reduction. Positive results show that optimized results with roll angle reduction are better than without. In the Fig. 6 it can be seen that this angular reduction contributes significantly to the power generation for several inclinations and all right ascensions.

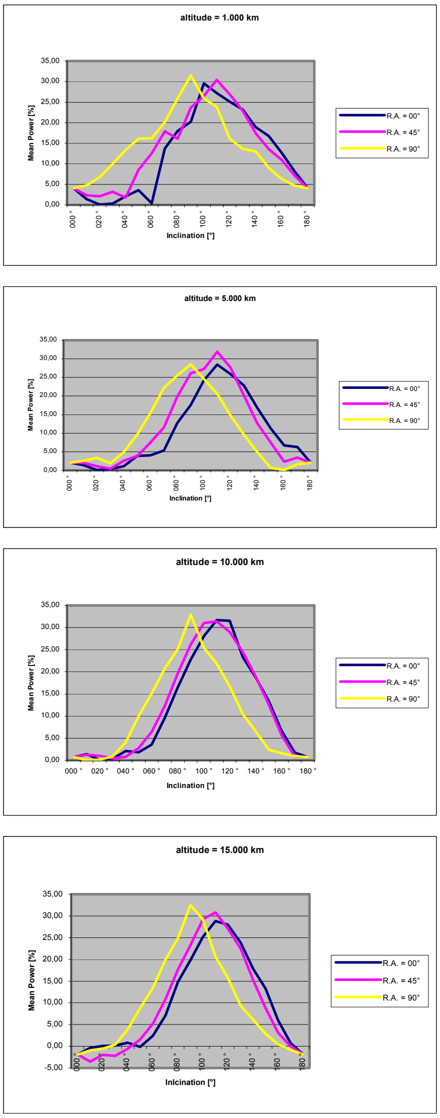

Fig. 5. Comparison of optimal power generation: ratio of optimized double-gimbaled solar array with simultaneous momentum management versus single axis solar-array.

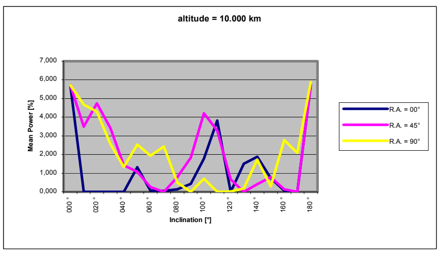

Fig. 6. Influence of local roll angle reduction control.

6. SUMMARY

A dual axis solar array mechanism is proposed for integrated momentum and power management making use of the gravity gradient torque for momentum unloading. An event based controller has been developed that combines power generation with momentum unloading by taking into account mission phases and needs. The event-based controller has three different operational states: one general for sun tracking, one for momentum unloading in eclipse, and one event for momentum unloading in the sun when a predefined momentum level is exceeded. For momentum unloading a time optimal control strategy is chosen to minimize the time for unloading. Additionally, the second angle tracking may be reduced to optimize the trade-off between momentum loading and power generation.

The mechanism kinematics together with the controller algorithm have been implemented in an analytic model environment which allows for solving the closed loop problem. All external torques such as gravity gradient, magnetic, solar pressure and aerodynamic torque are modeled. As the model is analytic it may be solved in rather short time such that parameter studies and optimizations can be performed in an efficient manner.

Results of parameter optimizations have been presented for different low-earth orbit scenarios. During system optimization the simulation time was at least one year to account for the seasonal changes of the elevation angle of the sun with respect to the orbit plane. For all optimized configurations found, it has been observed that not more than 10% of the maximum generable power (compared to a dual axis mechanism only used for sun tracking) has to be sacrificed for momentum control. Compared to a single axis mechanism a significant gain in power can be assumed (more than 30%).

Therefore, the proposed mechanism can be an attractive alternative on small satellites, where the classical subsystem approach may not be feasible anymore.

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