In-orbit attitude actuation using solar panels

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ABSTRACT
A specific technique is developed to wield the internal disturbance torque caused by the solar panel actuation for spacecraft attitude control tasks. This work is the maiden work towards integrating the attitude control and the solar tracking tasks, forming a combined attitude and solar tracking system. The feasibility of this concept for spacecraft is proven and eventually the combined concept is validated. A technical proof is presented corresponding to the end-to-end system demonstration. The investigation starts with the determination of the solar tracking constraints. Then, the mathematical models describing the attitude and solar tracking are established, and eventually the onboard architecture is implemented. The numerical treatments using Matlab^{TM} were performed to evaluate the developed onboard architecture. The simulation results are discussed especially from the attitude control standpoint. The integrated system complies very well with the reference mission requirements.

Keywords: Solar panel actuation; Attitude control systems; Spacecraft subsystems

1. INTRODUCTION

A novel multi-tasking spacecraft subsystem is desirable onboard a spacecraft to suppress its mass and volume budgets. Conventionally, the photovoltaic solar power generation method is employed in spacecraft. In small satellites, the solar cells are body-mounted, and therefore, the power generation capability is governed by the orbital motion. Instead, most high-end space missions have quite a significant power requirement. In this regards, the use of solar array drive assembly (SADA) is mandatory in order to constantly track the sun. The solar panels are constantly rotated using the DC motors. As a consequent, an internal disturbance torque is simultaneously generated, which has to be rejected in order to maintain the spacecraft's attitude accuracy. Typically, attitude actuators (e.g. reaction wheels, thrusters, magnetotorquers, etc.) are employed to generate the required torques to nullify the internal disturbance torque [1]. These actuators are also used to reject the external disturbance torques due to the aerodynamic, gravity gradient, solar radiation and the third body effects. In this work, the internal disturbance torque that is generated by the solar panels will be used to counter-act the external disturbance torque. In doing so, the attitude actuators are of no need, and therefore, the onboard mass and volume savings can be directly obtained [2].

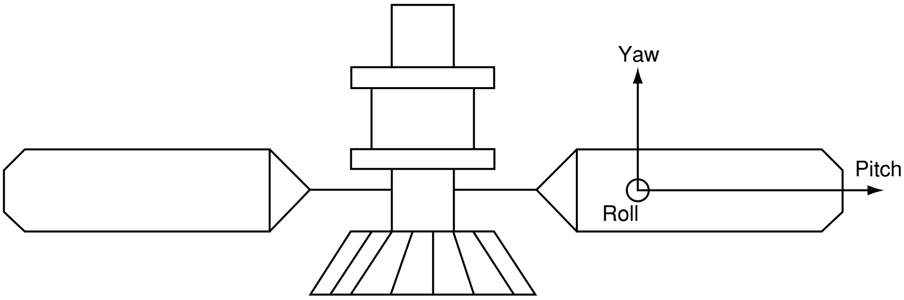

Figure 1 Solar panel configuration.

This novel concept can be extended to almost all space missions in low-earth-orbits (LEOs), medium-earth orbits (MEOs) and geostationary orbits (GEOs). In contrast, the solar sailing technique, which uses the solar radiation (i.e., solar protons) that hits the solar panels to perform attitude control, is exclusively for high altitude orbits such as the GEOs [3]. In addition, the solar sailing technique needs fairly large solar panels to receive the solar protons. Another disadvantage is that the solar sailing can only be performed during the sun phase. Due to this fact, the attitude actuators have to be still employed during the eclipse phase. Therefore, the solar sailing is employed in only a few satellites till to date.

2. SYSTEM DESCRIPTION

The integrated attitude and solar tracking system is an independent system derived from the existing solar array drive assembly (SADA) which includes a DC motor. Thus, additional hardwares are not required. The modification will be done in the control architecture of the solar panels in order to incorporate the satellite attitude control task. The solar panels are usually mounted along the Y (pitch) axis, whereby the X (roll) axis being the flight direction and Z (yaw) axis being normal to the orbital plane, see Fig. 1. Therefore, only the pitch axis is controllable through the solar panel actuations. The roll and yaw axis will be controlled by the conventional attitude actuators [4]. Thus, their control solutions are readily available and will not be discussed herein.

2.1. ATTITUDE AND POWER REQUIREMENTS

A reference mission is proposed to establish the attitude/power requirements and further to analyse the novel integrated system. The mission is as follows: 200 kg satellite with $1 \times 1 \times 1$ m^3 of volume, 5 years of mission duration, a circular orbit at 600 km with an inclination of 97.78°, pitch axis attitude accuracy of $< 0.2°$, and 166 W of power requirement [5]. The estimated external disturbance torques is $T_D = 6 + 10^{-6}$ Nm $+ 3 \times 10^{-5} (\sin \Omega_0 t)$ Nm.

Typically, the rotation of solar panels is within ±20° in order to generate a maximum solar power during the sun phase [5]. As a consequent, the in-orbit attitude control procedures should have a threshold of this value. It is obvious that the power requirement governs the attitude control task. The challenge for the attitude control system/loop is to produce the necessary control toques within the cumulative solar panel's rotational angle of less than ±20°.

3. SYSTEM ANALYSIS

The analytical calculation has to be done in order to estimate the onboard torque compartment for the reference mission. Then, the onboard integrated attitude and power tracking architecture will be implemented based on its governing equations. Thereafter, numerical treatments will be performed on the developed architecture to evaluate its performances.

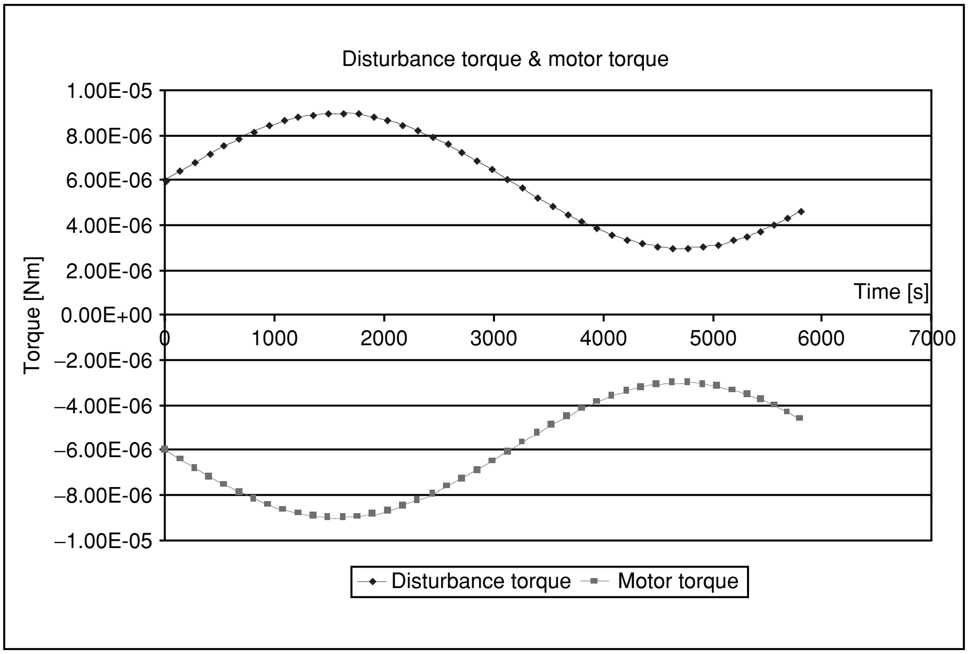

Figure 2 The system torque compartment.

3.1. ANALYTICAL EVALUATION

The total external disturbance torques for the reference mission is $T_D = 6 + 10^{-6}$ Nm + 3×10^{-5} (sin Ω_0t) Nm. Having this value, the required DC motor torque to compensate for the effect of the disturbances can be calculated. Subsequently, the accumulative angle of the panel orientation can be estimated to analyse the attitude performance. Only then the feasibility of this novel technique can be seen. Figure 2 shows the needed motor torques with respect to the external disturbance torques that need to be rejected. In addition, the rotation angle of the solar panel need to be estimated corresponding to the motor torques. It is important to mention that the idea is to determine if the solar panel rotation remains within the prescribed power constraint, i.e., the maximum rotational angle of ±20°.

With the values of desired motor torques, the solar panel's orientation and accumulative angles can be determined. Figure 3 shows the solar panel's orientation that is about ±1.5° each quarter of an orbit.

The corresponding accumulated angle due to the continuous internal torque generation is well below ±20°, see Fig. 4. It seems that the analytical calculation suggests that the technique is capable as an onboard attitude rejection solution. Therefore, the technique warrants further numerical testings.

3.2. NUMERICAL EVALUATION

Before the numerical analysis can be performed, the onboard attitude and power tracking architecture has to be implemented. The rotation of solar panels is controlled by the DC motor unit. The motor is operated in a speed mode in order to monitor the change in its rotational speeds, which is proportional to the generated onboard torque. The DC motor speed loop is shown in Fig. 5 together with its proportional controller K_m. Denoting s as the Laplace operator, the transfer function for the output panel speed Ω_m with respect to the speed command Ω_{cmd} is

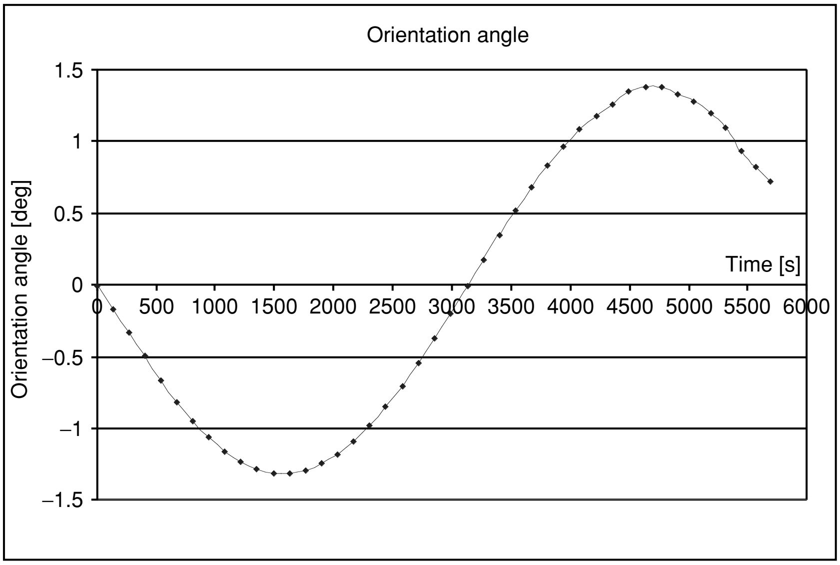

Figure 3 The solar panel's orientation angle.

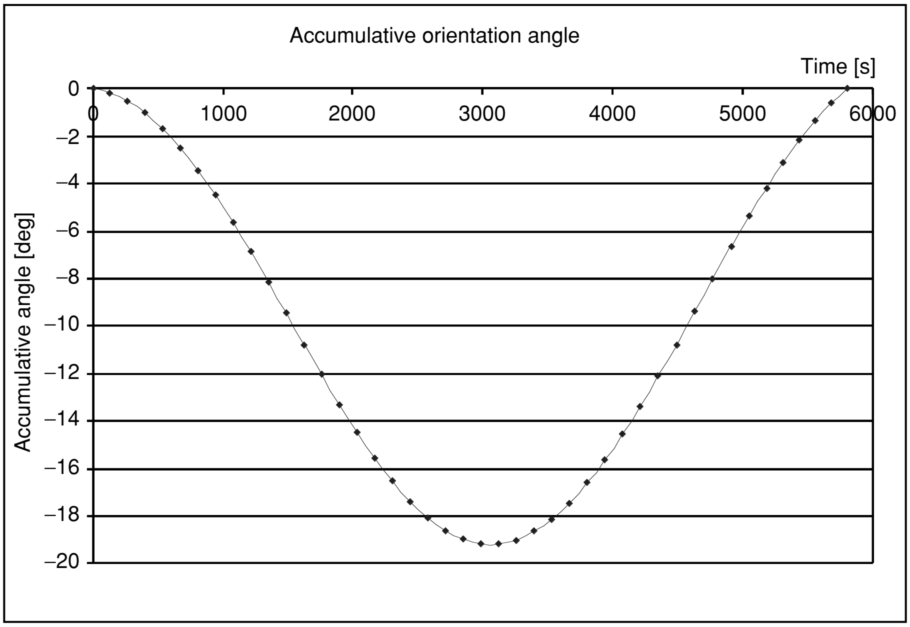

Figure 4 The solar panel's accumulated rotational angle.

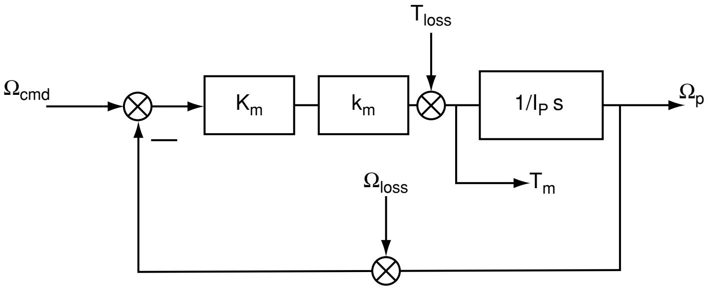

Figure 5 The DC motor control loop.

$$\frac{\Omega_m}{\Omega_{cmd}} = \frac{1}{1+\tau_m s} \tag{1}$$

where the speed loop delay is $$\tau_m = \frac{I_p}{K_m k_m} \tag{2}$$

whereby I_p is the panel's moment of inertia and k_m the motor torque constant.

The onboard torque generated by the motor yields

$$\frac{T_m}{\Omega_{cmd}} = \frac{I_p s}{1+\tau_m s} \tag{3}$$

The motor torque loss T_{loss} and the feedback speed loss Ω_{loss} in Fig. 5 are given 1% allowance each [6].

The onboard attitude control architecture is developed based on the linearized Euler equation of motion [4]. As mentioned before, the solar panels are mounted along the pitch (Y) axis, and therefore, only the pitch channel's dynamic will be discussed. The pitch control axis is closely aligned with its principal axis and the dynamic yields

$$I_y \ddot{\theta}_y + 3\Omega_0^2 (I_x - I_z)\theta_y = T_D - T_m \tag{4}$$

By applying the Laplace operator *s*, the pitch axis angular rate is

$$\dot{\theta}_y = \frac{T_D}{I_y s + 3\Omega_0^2 (I_x - I_z)/s} \tag{5}$$

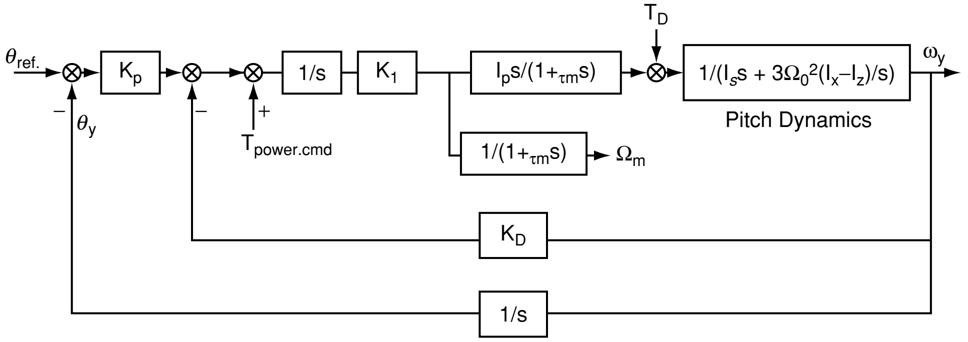

Figure 6 The onboard pitch attitude and power tracking architecture.

Figure 6 shows the developed pitch attitude and power tracking architecture. The PD type attitude control loop manages not only the pitch attitude command but only the power command torque command coming from the bus voltage regulation. The bus voltage regulation method is fairly standard and can be implemented as in Ref. 7. Letting the inertias as $I_x \approx I_y \approx I_z \approx I_s$ in Fig. 6, the pitch channel's complete dynamics simplifies to

$$\frac{\theta_y}{\theta_{ref.}} = \frac{1}{1 + \frac{K_D}{K_P}s + \frac{I_s}{K_P}s^2 + \frac{I_s \tau_m}{K_P}s^3} \tag{6}$$

The control parameter tunings with respect to the disturbance torques T_D can be done according to

$$\frac{\theta_y}{T_D} = \frac{1 + \tau_m s}{K_P + K_D s + I_m s^2 + \tau_m I_s s^3} \tag{7}$$

Evaluating Eq. (7) for a steady-state attitude response, the proportional attitude controller K_P can be estimated. Subsequently, the derivative attitude controller K_D is selected as well by evaluating Eq. (6) for a closed loop attitude stability. The stability analysis is done according to the pole-placement technique. Eventually, the developed attitude control architecture in Fig. 6 is amenable to numerical treatments using the Matlab-Simulink™ software [8]. The selected gains for the simulations are based on the reference mission given in section 2.1 are $K_P = 0.0025$ Nm/rad, $K_D = 1.4045$ Nms/rad, $K_1 = 1/I_p$ and k_m is regarded as unity so that the desired and exerted torque commands are directly proportional. The pitch axis's moment of inertia and the solar panel's moment of inertia are estimated to be $I_s \approx 109.3$ kgm^2 and $I_p \approx 2.4$ kgm^2, respectively. The flywheel speed loop delay τ_m is set to 2 s, and the pitch reference attitude is $\theta_{ref.} = 0°$.

Figure 7 shows the pitch attitude performance with respect to the orbital time. The pointing accuracy is very well below the mission requirement (<0.2°). The generated motor torques are shown in Fig. 8, which is similar to the values in Fig. 2.

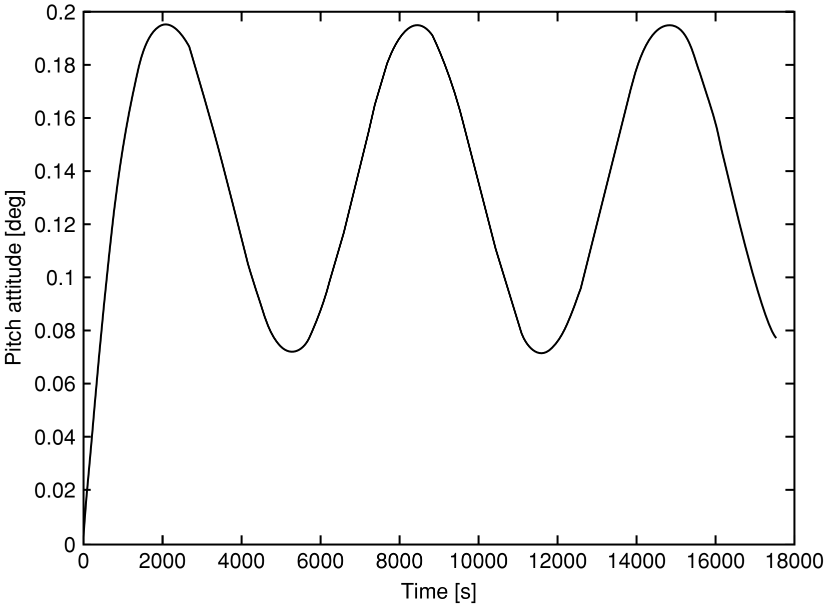

Figure 7 Pitch attitude accuracy.

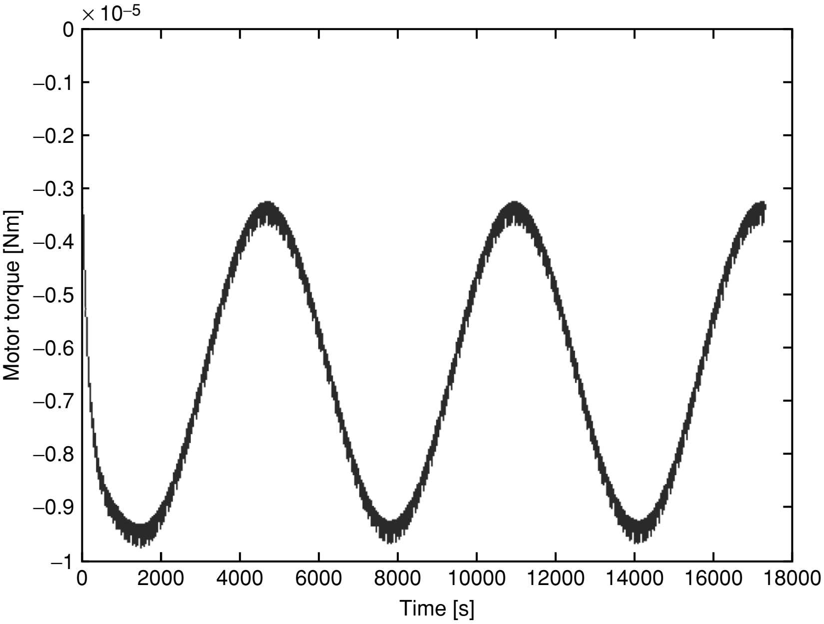

Figure 8 Generated motor torques.

4. CONCLUSIONS

This end-to-end system demonstration indicates that the integrated attitude and solar tracking concept is judiciously a feasible option and it can be easily implemented in spacecraft. The novel technique can readily be employed in space missions as a primary or secondary attitude actuator. The attitude pointing performance shown in this analysis fulfils the mission requirements. Hence, employing such an integrated system onboard spacecraft would benefit the mission itself, e.g., performance enhancements, mass and volume savings, etc.

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APPENDIX

NOMENCLATURE

K_P, K_D	proportional and derivative attitude control gains
K_m	proportional motor control gain
K_1	control gain
I_x, I_y, I_z, I_p, I_s	inertias
$T_{power.cmd}$	power torque command
T_D	external disturbance torques exerted on satellite
T_m	internal motor torques exerted on satellite
k_m	motor/generator torque constant
$\theta_{ref.}$	reference satellite attitude
θ_y	pitch satellite attitude
Ω_0	orbital frequency (0.001 rad/s)
Ω_m, ω_y	angular velocities