DESIGN AND TESTING OF MAGNETIC CONTROLLERS FOR SATELLITE STABILIZATION

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ABSTRACT
A study was carried out of attitude control algorithms that are able to provide 3-axis stabilization of a satellite equipped with a magnetometer as the only sensor and magneto-torquers as the only actuators. Two different solutions to the problem were developed, namely Linear Quadratic Regulator and No Wheel controllers. Their aptitude to achieve the required performance was confirmed by multiple numerical simulations under different initial conditions and various scenarios. The new algorithms were tested onboard the Israeli Gurwin-TechSAT micro-satellite, nominally momentum-biased, stabilized within 2°–2.5° precision by the proportion-plus-derivative magnetic controller. In the flight tests of the new controllers, some valuable results were obtained, such as revealing the possibility to effectively maintain the satellite 3-axis stabilization even with a very small momentum bias, and the implementation and efficient performance of the properly modified extended and linear Kalman filters in the onboard computer.

1. INTRODUCTION
Generally, in order to achieve precise stabilization by the magnetic control, the magneto-torquers (MTQ) in the satellite’s attitude control systems (ACS) are working together with other actuators, such as momentum or reaction wheels. The latter devices being costly and including rotating elements subject to failure, the advantages provided by the ACS without wheels are their robustness, reliability, low power consumption, and cost-efficiency. Furthermore, when proved effective, such purely magnetic control (PMC) algorithms could be considered as a contingency option in the ACS of the small satellites, flying alone, or in formations.

2. GURWIN-TECHSAT COMPASS CONTROLLER [1]
The 50-kg Israeli Gurwin-Techsat micro-satellite was put in an 820-km heliosynchronous orbit in July 1998, and has been successfully functioning for more than 4.5 years. Its ACS hardware includes a 3-axis magnetometer (MGM), a 3-axis magnetic torque coil set (MTQ), and the momentum wheel (MW). The satellite is 3-axis stabilized within 2°-2.5° precision by the proportion-plus-derivative COMPASS controller, as follows:

\[ \vec{m} = -K \cdot (\vec{B}_{\text{meas}} - \vec{B}_{\text{exp}}) + C \cdot (\vec{B}_{\text{meas}} - \vec{B}_{\text{exp}}) \]  

where \( \vec{m} \) is the control magnetic dipole moment, to be generated by the MTQ coils, \( \vec{B}_{\text{meas}} \) and \( \vec{B}_{\text{exp}} \) are the measured geomagnetic (GMF) vector and its derivative, referred to the Body Frame (BF), and \( \vec{B}_{\text{exp}} \) are the expected GMF vector and its derivative, referred to the Trajectory Frame (TF), the latter being also known as the orbit-following Local Level Frame.
3. LQR CONTROLLER [3]

The linearized model of the dynamical system under magnetic control can be described by the equation

$$\dot{\bar{x}} = A\bar{x} + \tilde{B}(t)\bar{m}$$

(2)

where \(\bar{x}\) is the process state vector, \(A\) the time-invariant system matrix, \(\tilde{B}\) the approximately periodic control effectiveness matrix, and \(\bar{m}\) the control magnetic dipole moment. By the periodic Linear Quadratic Regulator (LQR) technique, the solution to (2) was found in the form of the control law

$$\bar{m} = -R^{-1}\tilde{B}^T(t)P_{ss}\bar{x}$$

(3)

where \(P_{ss}\) is the asymptotic steady-state solution to the high-control-weighting time-dependent matrix Riccati equation, and \(R\) is the constant control weighting matrix. This LQR controller proved to be robust when full-state feedback is available. Making use of the constancy of the \(A\) matrix, and hence, of the state transition matrix, a linear Kalman filter (LKF) was included in the controller to provide it with the estimates of the state vector from MGM measurements. The controller (3) was optimized and supplied with the desaturation and Pulse Width Modulation (PWM) options to fit it to the Gurwin-Techsat MTQ, which might be either fully on, or fully off.

4. NO WHEEL CONTROLLER [3,4]

The control torque \(\bar{T}\), ensuring the satellite's stabilization without MW, can be calculated, according to the formula

$$\bar{T} = -(C_1\bar{\omega'} + C_2 I^{-1} \bar{\bar{q}})$$

(4)

where \(\bar{\omega'}\) is the instantaneous angular velocity of the BF with respect to the TF, as referred to BF axes; \(\bar{\bar{q}}\) is the attitude quaternion; and \(I\) is the satellite's diagonal tensor of inertia. Since in the magnetic ACS the control torque is implemented as a cross product of the relevant control dipole moment \(\bar{m}\) and GMF vector \(\bar{B}\):

$$\bar{m} = \bar{B} \times \bar{T}$$

(5)

in the "No Wheel" algorithm, instead of (4), the feasible control dipole moment \(\bar{m}\) was implemented, as follows:

$$\bar{m} = \frac{\bar{B} \times \bar{T}}{||\bar{B}||^2}$$

(6)

The vectors \(\bar{\omega'}\) and \(\bar{\bar{q}}\), entering (4), are estimated from the MGM measurements by the extended Kalman filter (EKF).

5. PLANNING THE FLIGHT TESTS

As mentioned, in the standard operating mode the Gurwin-TechSAT satellite is keeping its momentum bias \(H_w\) close to its nominal value (≈-0.42 Nm·s). Hence, testing the PMC algorithms should include the phase of slowing down and stopping the MW.

The simulated performance of the ACS with the LQR controller is shown in Figure 1, with the COMPASS-controlled 1st phase, comprising initial stabilization (0-20h), MW slowing down (40-55h), additional stabilization with LKF initialization (55-59h), followed by the LQR-controlled 2nd phase (starting at 59h).

In Figure 2, the simulation is represented of the ACS performance with NO WHEEL controller under scenario with COMPASS control phase (0h-78h), including EKF.
initialization and MW slowing down from $H_w$ nominal to $-0.005$ N·m·s under once-per-1 s control rate, and from $H_w = -0.005$ to $-0.0006$ N·m·s under once-per-10 s control rate; and NO WHEEL control phase (78 h–305 h), with MW stopping.

In both Figures, the parameters of the truth model are plotted in black, while those estimated either by LKF, or EKF – in light. As can be seen, the COMPASS control enables three-axis stabilization even with a very small momentum bias. The Kalman filters, which were properly modified to comply with the low performance capacity of the onboard computer, provide in both cases the adequate estimation of the state vectors and, thus, the convergence of the stabilization processes under purely magnetic control.

Figure 1. Simulation of slowing down MW and switching to LQR controller

Figure 2. Simulation of slowing down MW and switching to NO WHEEL controller

6. FLIGHT EXPERIMENTS
The flight experiments with both PMC algorithms were carried out according to the scenarios just outlined, with phases of gradual MW slowing down from nominal $H_w$ to zero and initialization of the relevant Kalman filter under COMPASS control, and switching to PMC controller. Seen in Figure 3 is the satellite's initially 3-axis stabilized attitude, even with zero $H_w$ (from the revolution No.17010 on), and its gradual deterioration, along with growing mismatch between the LKF (black) and ground estimator EKF (light dashed) estimates. The attitude angles increased to an extent when the LKF failed to perform adequately. Since the satellite's stabilization to a small-angle dynamics was not achieved, a switch to the LQR control couldn't be executed. Then, with $H_w$ being gradually built up, the stabilization was slowly restored, and so was the matching between the LKF and EKF estimates.

The onboard EKF telemetry of the NO WHEEL flight test is displayed in Figure 4. Under COMPASS control, the satellite kept 3-axis stabilization even with $H_w = -0.001$ N·m·s. Then, after MW turning off (at the revolution No.19020) and switching to NO WHEEL controller, the satellite's tumbling started, which could not be damped out.
7. CONCLUSIONS
Two PMC controllers were designed and tested, which should be able to provide 3-axis stabilization of the satellite without MW. In the course of their implementation on the Gurwin-Techsat satellite, an LKF and an EKF, adjusted to the onboard computer, were tested and displayed good performance, when compared with the independent MGM measurements processing by the ground estimator. During the flight tests, the ability of the COMPASS controller to maintain the satellite’s 3-axis stabilization with the next-to-zero momentum bias was confirmed. The attempts to activate the LQR and NO WHEEL controllers resulted in the satellite’s tumbling, which is believed to have been caused by the perturbing torques created by the currents in the MW coil, which affect the satellite’s attitude dynamics, and by the influence exerted by these currents on the magnetometer readings, when MW rotation speed is zero. Still, both PMC algorithms might perform well, when being actuated in the satellite without MW, or with MW kept fixed by a mechanical brake after the satellite’s release from the launcher.

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9. REFERENCES