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COMSAT 1.0 Software Aided Design for a Low Earth Orbit Microsatellite Commissioning Phase

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Abstract: In the past several years, a plethora of spacecraft control techniques have been developed that address the challenging attitude tracking, stabilization and disturbance rejection requirements of these missions. One major aspect that has been typically missing in the research area of attitude control development is the experimental validation of the theoretical results. Experimental testing is necessary before control laws can be incorporated in the future generation of spacecraft. Based on this fact, we thought on the implementation of a software design COMSAT 1.0 that has the ability to overcome these difficulties. It includes all the attitude control phases, from the launcher separation i.e., initial attitude acquisition until the accurate nadir attitude pointing. This software uses micro satellites i.e., small satellites as testing models in orbit. We have chosen Alsat-1 the first Algerian micro satellite as a test model.

Key words: Software, design, microsatellite, alsat-1, attitude, control, commissioning

INTRODUCTION

Immediately after separation from the final stage of the launcher, when place in it's low Earth orbit, the microsatellite can be tumbling at an undefined angular rate. The only attitude sensors useful at this stage will be the 3-axis magnetometer. A simple B-dot rate damping controller requiring only a Y-axis magnetic moment is used. This controller will reduce the X and Z-axis angular rates and align the microsatellite's to the orbit normal. The next step will be simultaneously control the Y-axis rate (Y-Thompson spin) to a fixed reference value. The orbit reference Y-axis (pitch) angular rate can be estimated from a simple pitch filter or Kalman rate filter. The pitch filter can be implemented once the satellite is in pure Y-Thompson spin. This filter will determine the pitch angle and rate using the magnetometer measurements and the modelled IGRF geomagnetic field vector (Si *et al*., 2005).

ATTITUDE DYNAMICS MODELLING

The dynamics of the spacecraft in inertial space is governed by Euler's equations of motion can be expressed as follows in vector form (Wertz, 1992; Hashida, 2004).

$$I\dot{\omega}^I_B = N_{GG} + N_D + N_M + N_T - \omega^I_B \times (I\omega^I_B + h) - h \qquad (1)$$

Where $\omega^I{}_B$, I, N_{GG}, N_D, N_M and N_T are respectively the inertially referenced body angular velocity vector, moment of inertia of spacecraft, gravity-gradient torque vector, applied magnetorquer control firing, unmodelled external disturbance torque vector such as aerodynamic or solar radiation pressure.

The rate of change of the quaternion is given by

$$\dot{q} = \frac{1}{2}\Lambda(q)\omega^O_B \qquad (2)$$

Where

$$\Lambda(q) = \begin{bmatrix} q_4 & -q_3 & q_2 \\ q_3 & q_4 & -q_1 \\ -q_2 & q_1 & q_4 \\ -q_1 & -q_2 & -q_3 \end{bmatrix} \qquad (3)$$

Where

$\omega^O_B = [\omega_{ox} \quad \omega_{oy} \quad \omega_{oz}]^T$ = body angular velocity vector referenced to orbital coordinates.

The angular body rates referenced to the orbit coordinates can be obtained from the inertially referenced body rates by using the transformation matrix A:

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$$\omega_B^O = \omega_B^I - A\omega_0 \tag{4}$$

If we assume the satellite in a near circular orbit with average orbital angular rate ω_o, then $\omega^B{}_0=[0-\omega_o\ 0]^T$ is a constant rate vector.

ATTITUDE DETERMINATION AND CONTROL SYSTEM DESCRIPTION

Small satellites have special requirements for attitude control systems, because power and mass are typically limited, but pointing requirements may, depending on the mission, still be tight. Most small satellites in low earth orbit use magnetic attitude control with either an air coil or a magnetorquer.

Magnetic attitude control provides small and limited torque without consuming valuable fuel.

One particular advantage of small satellites compared to larger spacecraft is the traditional lack of large, flexible appendices. At the same time, a truly rigid body provides little or no damping with respect to nutation and either active nutation damping or a passive damper is required.

Other aspects of small satellite attitude control are flexibility, survivability, graceful degradation in case of failures and simple controllers. Secondary payload opportunities may leave the satellite in an undesired attitude after deployment, possibly rotating at high rate. Single ground stations have only limited contact, requiring a higher degree of autonomy than larger satellites in geostationary orbit.

MAGNETOMETER

Three-axis flux gate magnetometers are used to measure the geomagnetic field vector in the satellite's body co-ordinates. These measurements are used to determine the torque vector generated when switching the magnetorquer coils. When used with a magnetic field model, magnetic measurement and model vectors can be fed to an extended Kalman filter to estimate the full attitude and angular rates of the satellite (Si *et al*., 2005). For a calibrated magnetometer, during periods of low solar activity, the attitude angles can be estimated to an accuracy of less than 1° per axis. The magnetometer can also be used when the satellite is still tumbling after the launch, to estimate the orbit referenced angular rates of the satellite body by using a rate Kalman filter. In-orbit calibration algorithms can be used to update the magnetometer scaling, offset and alignment errors in real time.

The Alsat-1 magnetometer characteristics are given by Si *et al*. (2003) (Table 1).

Table 1: Magnetometer on Alsat-1

Power	14 mA @ 12V 8 mA @ -12V
Range	-60 mT to +60 mT
Initial rate during detumbling	<0.1 deg $\sec^{-1}$
Full attitude/rate during mission	<0.5 deg $\sec^{-1}$
Dimension	130×90×36mm
Mass	295 grm
Thermal characteristics	- 50° C to +80° C

Table 2: Magnetorquer on Alsat-1

Power consumption	500 mW/Rod
Mass	500 grm
Dimension	250 ×607 ×38 mm
Thermal characteristics	-30°C to +60°C

MAGNETORQUER

The magnetorquers are coils through which a constant current can be switched. Both the polarity (direction) of these current can be controlled to generate on average a magnetic moment vector of any specific magnitude and direction within a defined time interval. The magnetic torquers on Alsat-1 are three magnetorquer rods let say X/Y/Z.

The magnetorquer will be used for the following control function on Alsat-1 (Si *et al*., 2004, 2005).

- Detumbling of the body angular rates after ejection from the launch vehicle;
- Control body spin around orbit normal;
- Libration damping when the gravity gradient boom is deployed;
- Yaw phase or yaw angular rate control when the gravity gradient boom is deployed;
- Momentum management of the reaction/momentum wheels;

Magnetorquers can be designed to provide momentum management on a low earth orbiting spacecraft. Dipole moments generated by the magnetorquer interact with the Earth's magnetic field to generate small torques on the spacecraft. Since the magnetic torque is always orthogonal to the local magnetic field vector, it is not possible to generate instantaneously a required torque direction as demanded by a full 3-axis control system. However, in the course of an orbit the direction of the vector may change and it may be possible to generate the required torque on average during the course of an orbit. A consistent and reasonable strength vector is available only in low earth orbits.

The Alsat-1 magnetorquer characteristics are given by Si *et al*. (2003) (Table 2).

CONTROLLERS

Called despin, this controller directly requires no attitude or rate information (Si *et al.*, 2005). The controller is implemented by measuring the magnetic field vector every 10 sec and firing the M_Y magnetorquer for short periods at the correct polarity depending on the angular rate of the magnetic field vector (Martel *et al.*, 1998; Si *et al.*, 2006).

A magnetic torquer along the desired spin axis (Y-axis) is controlled such that

$$M_y = K_d \dot{\beta} \quad \dot{\beta} = \mathrm{acos}\left(\frac{B_y}{\|B\|}\right) \tag{5}$$

Where K_d a constant gain parameter.

The next step will be simultaneously control the Y-axis rate (Y-Thompson spin) to a fixed reference value (Si *et al.*, 2005). A certain reference Y-spin rate ($\omega_{oy\text{-}ref}$) can be controlled by using the X-axis torquer (Si *et al.*, 2005) as follows

$$M_x = K_s(\omega_{oy} - \omega_{oy\text{-}ref})\mathrm{sgn}(B_z) \tag{6}$$

Where K_s a constant gain parameter.

The orbit reference Y-axis (pitch) angular rate (ω_{oy}) can be estimated from a pitch filter or Kalman rate filter. The reference Y-axis body rate ($\omega_{oy\text{-}ref}$) is chosen to be - 1 deg sec^{-1} to give a stable angular momentum vector.

NUMERICAL SIMULATION METHODOLOGY

Figure 1 presents the software simulator diagram and structure including orbit propagator Standard General Propagator SGP4, attitude propagator including external torques and finally the control modes. A 98° inclination, circular orbit at an altitude of 860 km was used during the simulation tests.

Figure 2 presents the attitude simulator that implements the dynamic and kinematics of the satellite Eq. 1-4. The satellite dynamics are modelled using Euler's equation for a rigid body motion under the influence of internal and external torque.

Figure 3 presents the different control modes such as B-dot controller, Y-Thompson spin before boom deployment.

Figure 4 and 5 presents a graphical user interface in which the output data of different parameters such as initial orbit (circular), initial attitude [0 0 0] degree and attitude rate ω_{bo} =[5 -8 -7]^T deg sec^{-1}, inertia and control parameters (wheel and magnetorquer).

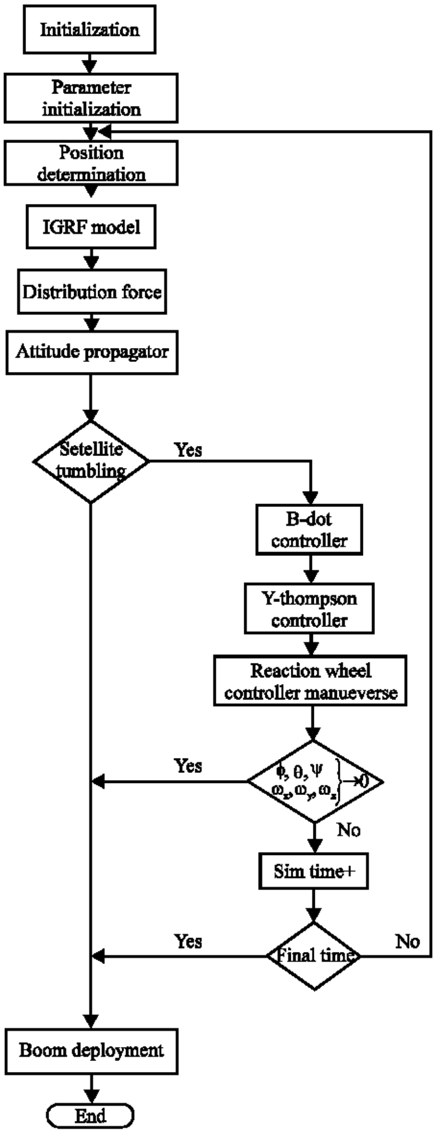


Fig. 1: Software simulator structure

Figure 6 presents the performance of the B-dot controller, Y-Thompson from initial tumbling to Nadir attitude pointing. The initial orbit referenced angular rate vector ω_{bo} =[5 -8 -7]^T deg sec^{-1}. The spin damping controller of Eq. 5 is immediately enabled. After two orbits (12000 sec) the Y spin controller of Eq. 6 is enabled. The Y axis body rate is controlled to -1 deg sec^{-1}. The target rate is reached after 3 orbits (18000 sec).

Figure 7 presents the gravity gradient torque and the earth magnetic field from initial tumbling to Nadir attitude pointing. A 10th Order IGRF B-field model from (Wertz, 1992) was used to obtain the geomagnetic field values. The activity of the measured magnetic field is due to the the magnetorquer activity and the average power consumption from initial tumbling to Nadir attitude pointing.

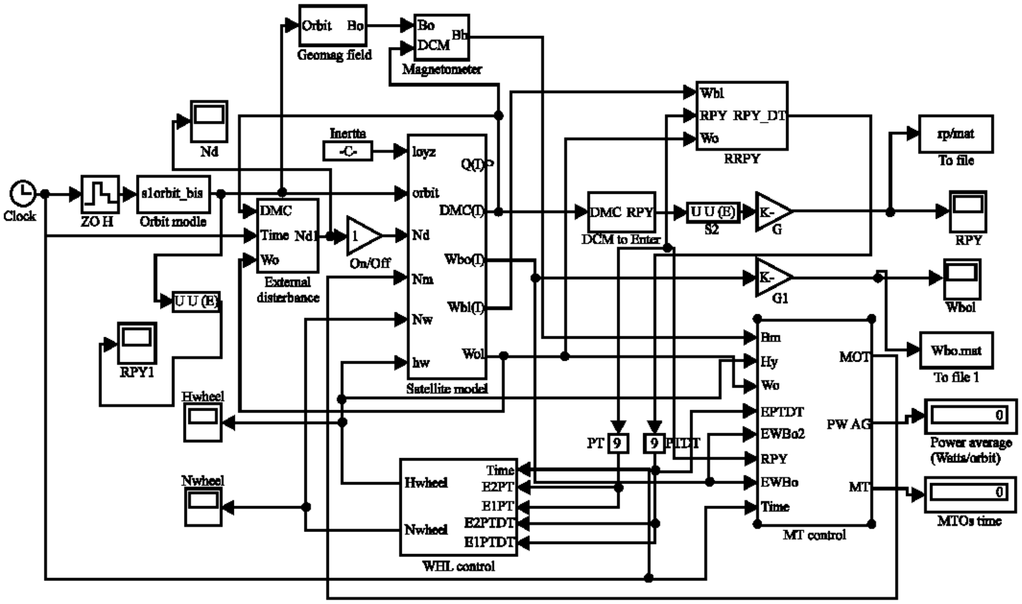


Fig. 2: Attitude simulator simulink model

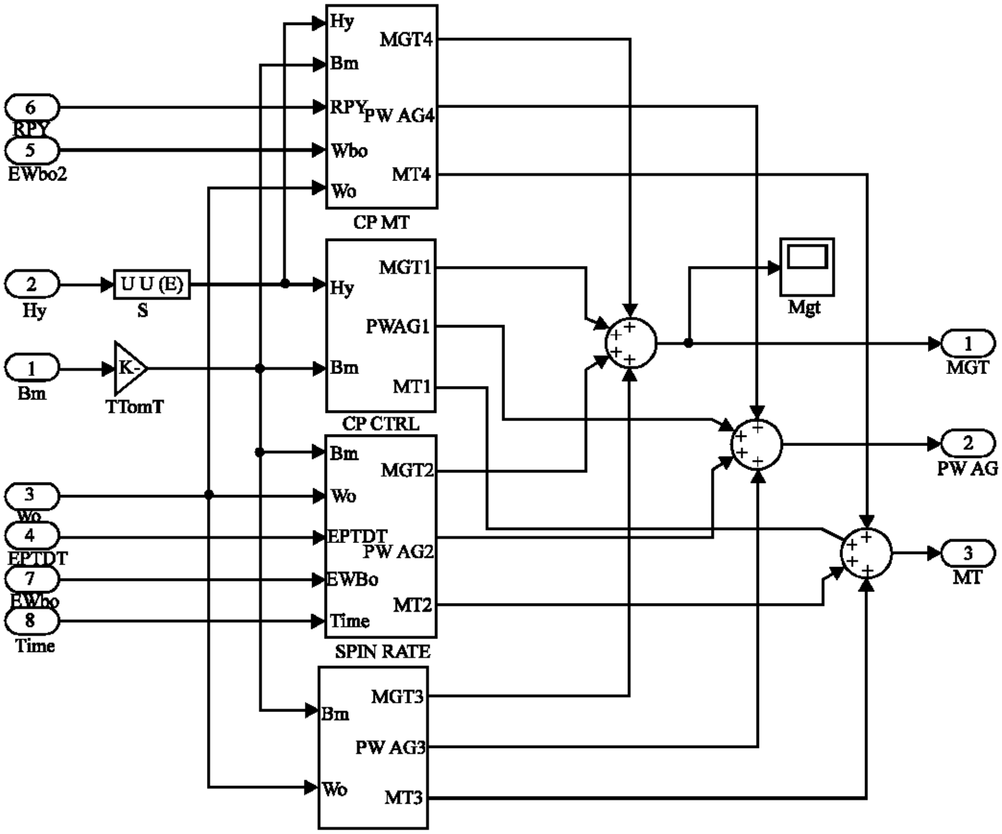
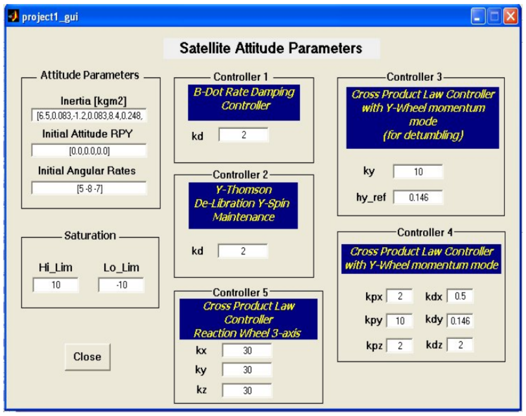


Fig. 3: Post boom deployment simulator



project1_gui

Satellite Attitude Parameters

Attitude Parameters

Inertia [kgm2]: [6.5,0.083,-1.2,0.083,8.4,0.248,

Initial Attitude RPY: [0.0,0.0,0.0]

Initial Angular Rates: [5 -8 -7]

Saturation

Hi_Lim: 10

Lo_Lim: -10

Controller 1 — B-Dot Rate Damping Controller

kd: 2

Controller 2 — Y-Thomson De-Libration Y-Spin Maintenance

kd: 2

Controller 3 — Cross Product Law Controller with Y-Wheel momentum mode (for detumbling)

ky: 10

hy_ref: 0.146

Controller 4 — Cross Product Law Controller with Y-Wheel momentum mode

kpx: 2

kdx: 0.5

kpy: 10

kdy: 0.146

kpz: 2

kdz: 2

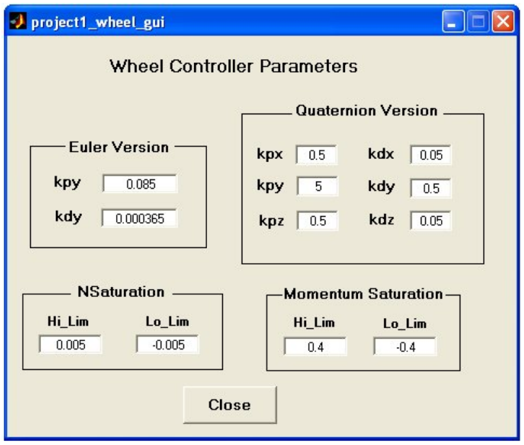
Controller 5 — Cross Product Law Controller Reaction Wheel 3-axis

kx: 30

ky: 30

kz: 30

Fig. 4: Satellite parameter initialization GUI



project1_wheel_gui

Wheel Controller Parameters

Euler Version

kpy: 0.085

kdy: 0.000365

Quaternion Version

kpx: 0.5

kdx: 0.05

kpy: 5

kdy: 0.5

kpz: 0.5

kdz: 0.05

NSaturation

Hi_Lim: 0.005

Lo_Lim: -0.005

Momentum Saturation

Hi_Lim: 0.4

Lo_Lim: -0.4

Fig. 5: Reaction wheel parameters GUI

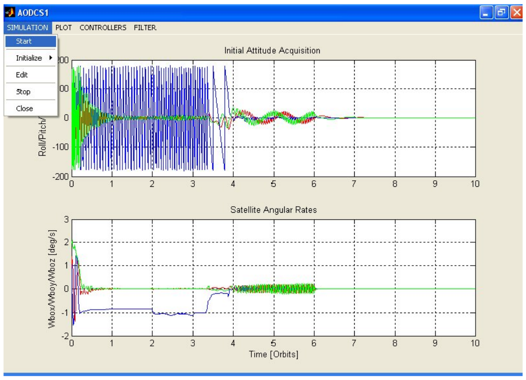


Fig. 6: Attitude and angular rates

Figure 8 presents the magnetorquer activity and the average power consumption from initial tumbling to Nadir attitude pointing. The total accumulated on-time magnetorquer coils used, is approximately 11500 sec during a active control windows of basically 3 orbits (18000 sec). This gives an average magnetorquer power drain of 15 Watt from the starting of Detumbling until the Y-Thompson attitude achieved.

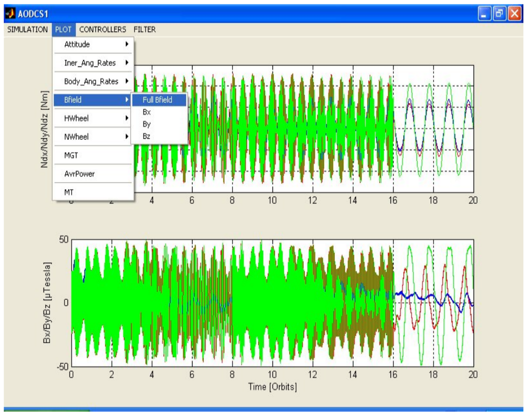


Fig. 7: External disturbance torques and the earth magnetic field representation

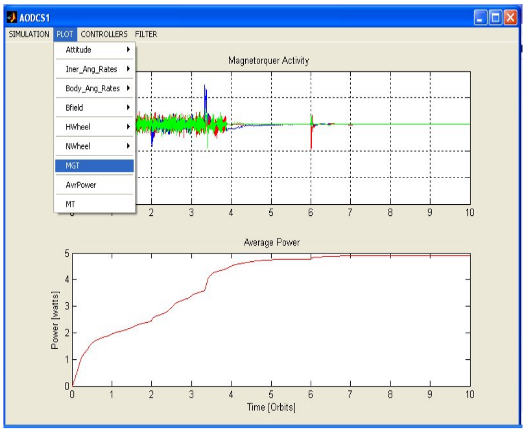


Fig. 8: Magnetorquer activity and the average power consumption

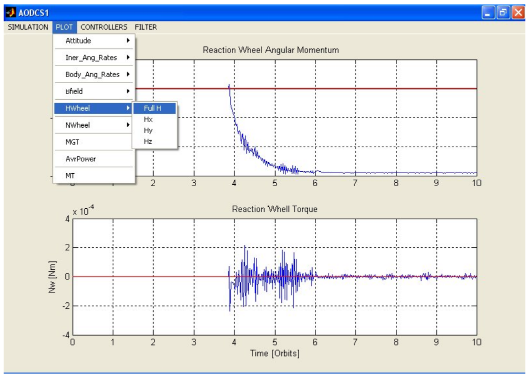


Fig. 9: The angular momentum and the torque generated by the reaction wheel

Figure 9 show the implementation of the Y wheel to absorb the Y body momentum and stabilise the satellite into Nadir attitude pointing. During the first orbit the satellite is in perfect Y-Thompson spin. At the start of the second orbit the Y wheel is ramp to a momentum of -0.6 Nms using the open loop strategy. The Y body rate is slowed from -1 deg sec^{-1} to 0.2 deg sec^{-1} as the satellite body momentum is absorbed by the wheel. After 1500 sec the wheel reached its target of -750 RPM (-0.6 Nms) and the speed is kept constant to allow the pitch angle to drift towards the Nadir. When the pitch angle is within 10 degree from Nadir, the pitch wheel controller and the cross product wheel controller are enabled.

CONCLUSION

The attitude control system development process can be a major cost and risk driver for any mission. This software design is a versatile and powerful tool that integrates and simplifies the attitude control system design, development, test and different maneuvers operation processes. It has several improvements over existing designs. One possible improvement to the simulation would be a Graphical User Interface (GUI) which allows the user to view the output data as the simulation is progressing. A GUI could also allow command lists to be sent at any time during the simulation, increasing the value of the simulation as an operator training tool.

This software was used for Alsat-1 and the initial results show good performance from the magnetometers and magnetorquers.

This version presented needs to include Rate Kalman Filter and the Pitch Filter.

The development presented in the COMSAT 1.0 software allows us to:

- Experimental validation of the theoretical results;
- Get use for training program and education to space techniques;
- It will help Algeria to acquire satellite design and learn spacecraft technology.

REFERENCES

Hashida,Y., 2004. ADCS Design for future UoSAT standard platform. Surrey Space Centre, Guilford, UK, Chapter 2, SSTL Internal Report, pp: 19-20.

Martel, F., P.K. Pal and M. Psiaki, 1998. Active Magnetic Control System for Gravity Gradient Stabilized Spacecraft. Proceeding. of the 20th AIAA/USU Conference on Small Satellites, Utah State University, USA.

Si Mohammed, A.M., M. Benyettou, M.N. Sweeting and J.R. Cooksley, 2005. Initial attitude acquisition result of the alsat-1 first algerian microsatellite in orbit. Proc IEEE International Conference on Networking, Sensing and Control, Tucson, Arizona, USA., pp: 566-571.

Si Mohammed, A.M., M. Benyettou, M.N. Sweeting and J.R. Cooksley, 2005. Full Attitude Determination Specification - Small Libration Version- of the Alsat-1 First Algerian Microsatellite in Orbit. Proc. IEEE Recent Advances in Space Technologies, RAST Istumbul, Turkey, pp: 150-154.

Si Mohammed, A.M., M. Benyettou, M.N. Sweeting and J.R. Cooksley, 2005. Imaging mode results of the alsat-1 first algerian microsatellite in orbit. Proc. IEEE. Recent Adv. Space Tech. RAST. Istunbul, Turkey, pp: 483-486.

Si Mohammed, A.M., M. Benyettou, M.N. Sweeting and J.R. Cooksley, 2006. Wheel Attitude Cancellation Thruster Torque of LEO Microsatellite during Orbital Maintenance, Asian Network for Scientific Information, J. Applied Sci., 6: 2245-2250.

Si Mohammed, A.M., M.N. Sweeting and J.R. Cooksley, 2004. Modelling and Simulation of Magnetic Control and its Application on Alsat-1 First Algerian Microsatellite. Proc. 18th European Simulation Multiconference, Networked Simulations and Simulated Networks, SCS- The Society for Modeling and Simulation International, Magdeburg, Germany, pp: 296-300.

Si Mohammed, A.M., M.N. Sweeting and J. R. Cooksley, 2003. An attitude determination and control system of the alsat-1 first algerian microsatellite", Proc. IEEE. Recent Adv. Space Tech. RAST. Istumbul, Turkey, pp: 162-167.