Theoretical and Numerical Analysis of the Attitude Control of a 3U CubeSat - Iraqi Satellite (TIGRISAT)

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Abstract:-

TIGRISAT is a small satellite, three units (3U) CubeSat which has a mission concerned to dust storms observation. For this purpose, Earth's Nadir pointing has been applied to achieve that mission. The attitude determination and control system (ADCS) must have the capability to provide continuous roll ($\emptyset$), pitch (θ), and yaw (ψ) steering. Hence, Nadir pointing set to be at (x − axis) of TIGRISAT where the camera is fixed, and roll angle govern this axis.

While TIGRISAT is a small satellite with a low weight (4Kg), torque coils used to generate magnetic dipole moment for attitude and angular momentum control. They are also used to compensate the residual spacecraft biases and to counteract the attitude drift due to environmental disturbance torques. Two pair of coils have been used for each axis. Each side coil has (220 turn), while the upper and lower coil has (320 turn) for each one. The maximum torque produced by these coils is (0.0386 N.m) and this value of torque is quite enough to overcome the total disturbance torques and to provide the desired orientation. An algorithm has been designed to produce a magnetic dipole moment that is constantly orthogonal to the geomagnetic field vector, independently of the attitude and the angular rate of the rigid spacecraft. This algorithm gives the current needed to stabilize each axis of TIGRISAT, power consumption, kinetic energy, and the angular rates.

Keywords: - TIGRISAT, CubeSat, Nadir pointing, Torque coils, B-dot Algorithm.

1- Introduction:

In 1999 Prof. Jordi Puig-Suari at California Polytechnic State University (Cal Poly) and Prof. Bob Twiggs at Stanford University's Space Systems Development Laboratory (SSDL) started the CubeSat program [17]. The CubeSat design has standard dimension represented by ($10\ cm \times 10\ cm \times 10\ cm$) cube, also referred to as one unit (1U) CubeSat.

TIGRISAT is three units CubeSat (3U), it is also the first Iraqi Satellite launched into space. TIGRISAT has been designed and built with the cooperation of Sapienza University of Rome in Italy in 2012, then launched into space (Low Earth Orbit) in 19 June 2014 from Yasny base Southern Russia using Dnepr launch vehicle and released in orbit in 20 June 2014 at 2107 UTC- 25 hours and 38 minutes. According to payload needs, a precise pointing is often requested. Many satellites are intended to be Earth oriented and the others are intended to face the sun or certain stars of interest. Often one part of a spacecraft such as a communication antenna, must point toward Earth, while another part such as solar panel must face the sun. To achieve such mission objectives, it is evident that an attitude stabilization and control system must be an important part of spacecraft design. Thus, the main purpose of the attitude control system (ACS) is to orientate the main structure of the spacecraft correctly and with the required accuracy. Attitude stabilization maintain an existing attitude relative to some external reference frame such as inertial fixed or slowly rotating, as in the case of Earth-oriented satellites.

Control system can be applied using either an active or passive control system. In the active control system, continuous decision and specific hardware are required. The most common sources of torque for active control systems are gas jets, electromagnets, and reaction wheels. While the gravity gradient and permanent magnets are common passive attitude control methods.

The decision to use passive or an active control system or combinations of the two systems depends on the mission pointing and stability requirements, interaction of the control system with onboard experiments or equipment, power requirements, weight restrictions, mission orbital characteristics, and the control system stability and response time.

For near Earth orbit, spin-stabilized spacecraft, magnetic coils commonly used for attitude maneuvers and periodic adjustment of the spin rate and attitude, while above synchronous altitudes, gas jets would be required for these functions because the Earth's magnetic field is generally too weak [8]. However, when a satellite is in orbit, gravity is the only force acting on it (if we neglect the secondary drag forces and the gravitational influence of bodies other than the planet being orbited), also unless the satellite is unusually large. In this case, the gravitational force is concentrated at the center of mass (C.M). Since the net moment about the center of mass is zero, the satellite is "torque free" [6]. Since TIGRISAT orbited in low Earth orbit with an altitude (600.2 km) and it has a mission (Dust Observation) which requires nadir pointing strategy, an active control system using torque coils method has been applied. Controlling the satellite's attitude via magnetic actuators alone is an attractive option, because the compact in size, have no moving parts, and consume only electricity, which can be supplied by batteries and solar panels. The drawback to purely magnetic actuation, however, is that the system is instantaneously under actuated due to the inability to exert a torque parallel to the direction of the magnetic field vector. However, unlike under actuated systems involving reaction wheel or thruster failures [5]-[2], in this system the unactuated axis is not fixed with respect to the body but rotates as the satellite traverses its orbit. System controllability is obtained by taking advantage of the time varying unactuated axis in tandem with the gravity gradient torque.

Much prior work has been done to investigate the use of magnetic torques in spacecraft attitude control. However, that work has largely focused on the use of magnetic torque in spin stabilize spacecraft [9], [7] or in gravity gradient stabilize spacecraft [15], [20].

2- TIGRISAT Specifications and Dimensions:

The initial conditions and dimensions of TIGRISAT are listed in **Table.1** as follows

Table.1 TIGRISAT Specifications and Dimensions

Orbit Properties	
Altitude	600.2 km
Eccentricity	0.003
Inclination	97.79°
Type of orbit	Low earth orbit (LEO) Sun-synchronous orbit
Pointing	Nadir pointing at the body axis x_b aligned to the radial direction $\hat{r}$
Dimensions	
X	30 cm
Y	10 cm
Z	10 cm
Weight	
4 kg	
Moment of Inertia	
I_x	$6.667 * 10^{-3}\ (kg.m^2)$
I_y	$0.0333\ (kg.m^2)$
I_z	$0.0333\ (kg.m^2)$
Coils	

No. of turns at x-axis	320
No. of turns at y-axis	220
No. of turns at z-axis	220
Coil area at x-axis	0.003 m^2
Coil area at y-axis	0.01485 m^2
Coil area at z-axis	0.01485 m^2
Max. current	0.3 A

Fig .1 below shows TIGRISAT's layout with the chosen system coordinates illustrated on it

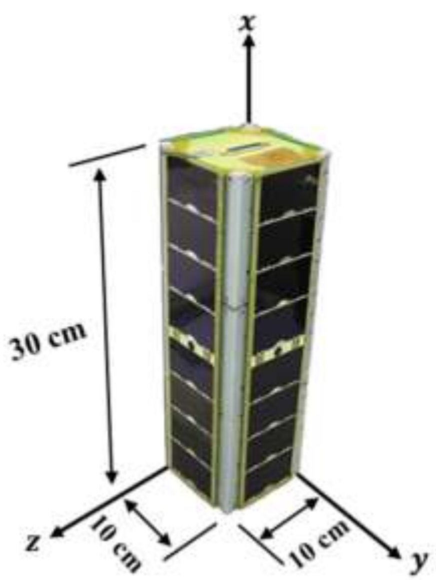


Fig.1 TIGRISAT's layout

3- Mathematical models for the attitude motion

a. Coordinate systems

To define the attitude of any satellite in a space, two right-handed rectangular systems, should be employed. In our case (TIGRISAT), the nadir pointing strategy is required on the body axis (x_b) where the camera is fixed. When the attitude error is zero, the body reference frame (x_b, y_b, z_b) would overlap the orbital reference frame $(\hat{e}, \hat{p}, \hat{h})$. The two coordinates systems are shown in **Fig.2** below.

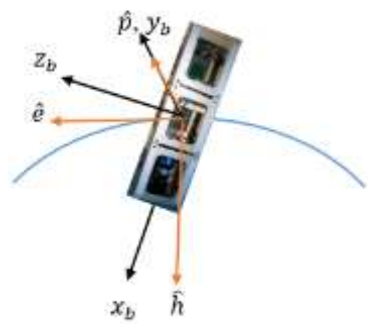


Fig. 2 Schematic sketch of the body fixed frame, and orbital reference frame.

The earth reference frame (initial reference frame) should be also employed to determine the orbit and the reference vectors.

b. Euler angles

Three angles are required to specify the orientation of a rigid body relative to an inertial reference frame, in fact, the choice is not unique. If we define the three orthogonal axes of the body frame by $(\hat{x}_b, \hat{y}_b, \hat{z}_b)$, and other three in the Earth fixed frame $(\hat{C}_1, \hat{C}_2, \hat{C}_3)$. There is a multitude of ordered combinations by which the rotation can be performed. For instance we might first perform a rotation about $(\hat{x}_b)$, then about $(\hat{y}_b)$, and finally about the $(\hat{z}_b)$ axis. The order of rotation could also be about $(\hat{y}_b, \hat{x}_b, \hat{z}_b)$ and so on.

In fact, there are two distinct types of rotations:

1- Successive rotations about each of three axis $(\hat{x}_b, \hat{y}_b, \hat{z}_b)$. There are six possible orders of such a rotation: (1-2-3), (1-3-2), (2-1-3), (2-3-1), (3-1-2) and (3-2-1).

2- First and third rotations about the same axis with the second rotation about one of the two remaining axes. In this case, also we have six possibilities of rotations, which is: (1-2-1), (1-3-1), (2-1-2), (2-3-2), (3-1-3), and (3-2-3) **[11].**

The second type of rotation sequences affected by singularities, thus, it is better to use the first type of rotation sequences because, all the axes are different, and then, no singularities arise. In TIGRISAT, the most commonly used order $(\emptyset, \theta, \psi)$ chose to specify the orientation, where $(\emptyset)$, is Euler roll angle that define the rotation about the body axis $(\hat{x}_b)$, while pitch

angle (θ) define the rotation about the body axis $(\hat{y}_b)$, and yaw angle (ψ), define the rotation about the third body axis $(\hat{z}_b)$.

Where:

$$R_1(\phi) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & cos_\phi & sin_\phi \\ 0 & -sin_\phi & cos_\phi \end{bmatrix}$$

$$R_2(\theta) = \begin{bmatrix} cos_\theta & 0 & -sin_\theta \\ 0 & 1 & 0 \\ sin_\theta & 0 & cos_\theta \end{bmatrix} \qquad (1)$$

$$R_3(\psi) = \begin{bmatrix} cos_\psi & sin_\psi & 0 \\ -sin_\psi & cos_\psi & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

The orientation of the body frame with respect to the Earth fixed frame results in an orthogonal transformation. Final rotation matrix obtained by multiplying the three rotations matrices above, considering the reverse direction in multiplication as it shown below (2).

$$\mathrm{R} = R_3(\psi)\, R_2(\theta)\, R_1(\phi)$$

$$R = \begin{bmatrix} cos_\theta cos_\psi & sin_\phi sin_\theta cos_\psi + sin_\psi cos_\phi & -cos_\phi sin_\theta cos_\psi + sin_\psi sin_\phi \\ -cos_\theta sin_\psi & -sin_\phi sin_\theta sin_\psi + cos_\psi cos_\phi & cos_\phi sin_\theta sin_\psi + cos_\psi sin_\phi \\ sin_\theta & -sin_\phi cos_\theta & cos_\phi cos_\theta \end{bmatrix} \quad (2)$$

The four rotations matrices above can be illustrated in **Fig.3** as it follows;

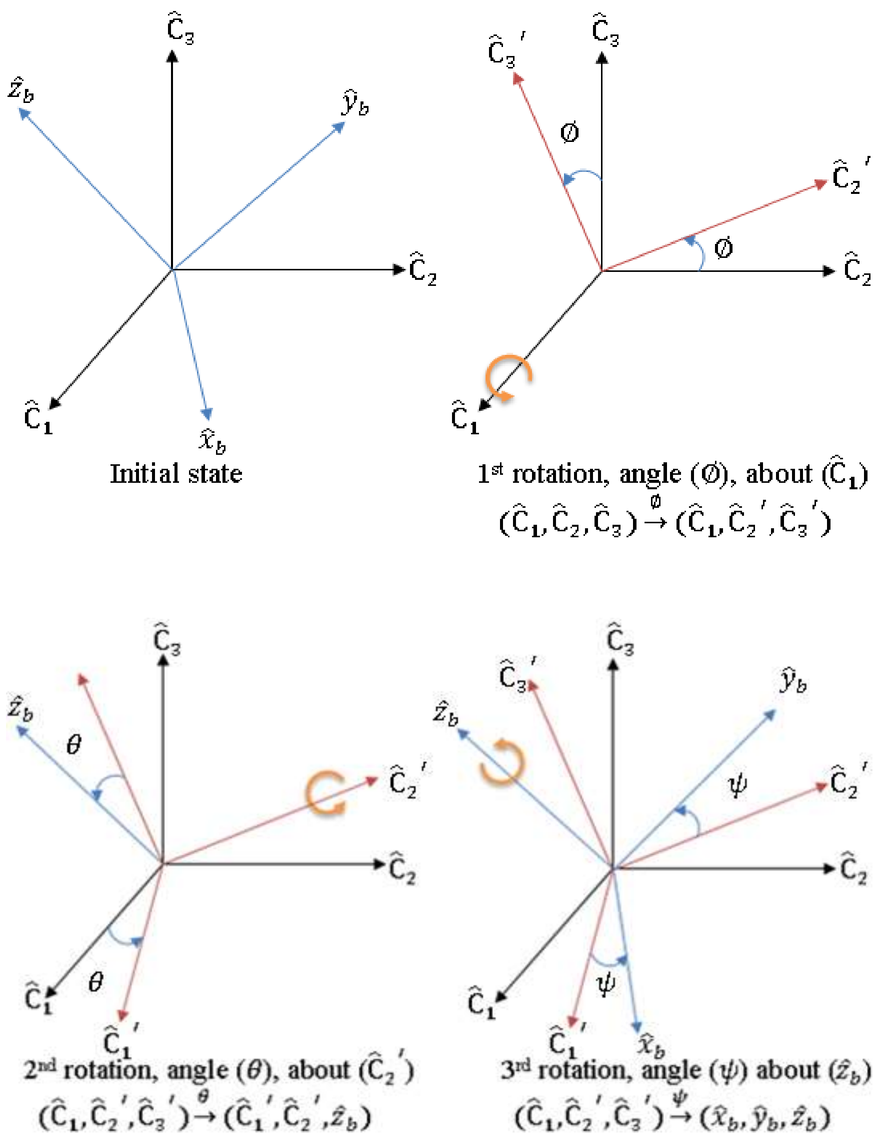


Fig.3 Euler angles sequence (1-2-3) - ($\emptyset, \theta, \psi$)

The sequence of rotation above represent the body reference frame of the satellite $(\hat{x}_b, \hat{y}_b, \hat{z}_b)$ with respect to the Earth fixed frame $(\hat{C}_1, \hat{C}_2, \hat{C}_3)$.

c. Mathematical model of the Dynamics Equations of Motion

The basic equation of attitude dynamics relates the time derivatives of the angular momentum vector, $d\vec{\Gamma}/dt$ to the applied torque $(\vec{T})$. In this section, the time derivative of the components of the angular momentum $(\vec{\Gamma})$ expressed along TIGRISAT body axes $(\hat{x}_b, \hat{y}_b, \hat{z}_b)$.

In fact, the inertia tensor of a rigid body is constant in body frame. Since the angular momentum is defined as

$$\vec{\Gamma} = I\vec{\omega} \quad (3)$$

Starting from the second fundamental equation of dynamics (**Euler's 2nd Law**) which states that the rate of change of the angular momentum $(\frac{d}{dt}\vec{\Gamma})$ about an axis is equal to the sum of the external moments of force (Torques) about that point **[16]**.

$$\frac{d}{dt}\vec{\Gamma} = \vec{T} \quad (4)$$

Since the angular velocity between the satellite body frame and an inertial frame written on the body frame, as well as, the inertia tensor is a constant in the body frame for the reason mentioned above, thus the derivative of the angular momentum in equation (3) is;

$$\frac{d}{dt}\vec{\Gamma} = \dot{\vec{\Gamma}} + \vec{\omega} \wedge \vec{\Gamma} \quad (5)$$

Then, by substituting equation (3) into equation (5), that gives;

$$\frac{d}{dt}\vec{\Gamma} = I\dot{\vec{\omega}} + \vec{\omega} \wedge I\vec{\omega} \quad (6)$$

Hence, equation (6) called attitude Euler equation.

Now substitute equation (4) into equation (6) to obtain

$$\vec{T} = I\dot{\vec{\omega}} + \vec{\omega} \wedge I\vec{\omega} \quad (7)$$

The components of the angular velocity in the body frame of the spacecraft presented as it follows

$$\vec{\omega} = \omega_x\hat{x}_b + \omega_y\hat{y}_b + \omega_z\hat{z}_b \quad (8)$$

Thus, $(\vec{\omega} \wedge I\vec{\omega})$ can be written as

$$\vec{\omega} \wedge I\vec{\omega} = \begin{bmatrix} \hat{x}_b & \hat{y}_b & \hat{z}_b \\ \omega_x & \omega_y & \omega_z \\ I_x\omega_x & I_y\omega_y & I_z\omega_z \end{bmatrix} \quad (9)$$

The determinant of matrix (9) estimated along the first row using Laplace method.

Equation (7) written in component form when the vector quantities referred to the principal axis coordinate system in order to simplify the equation of motion. Then, If two principal moment of inertia are equal, such as (I_x) and (I_y), that is referred to the axial symmetry case.

In the principal axis, system equation (7) has the components

$$I_x\,\dot{\omega}_x + \left(I_z - I_y\right)\omega_y\omega_z = T_x \quad (10)$$

$$I_y\,\dot{\omega}_y + (I_x - I_z)\omega_x\omega_z = T_y \quad (11)$$

$$I_z\,\dot{\omega}_z + \left(I_y - I_x\right)\omega_x\omega_y = T_z \quad (12)$$

Euler's equations of motion employed to discuss the stability of rotation about principal axis of a spacecraft. If the spinning is on $(\hat{z}_b - \text{axis})$ of the spacecraft, so that (ω_x) and (ω_y) are much smaller than (ω_z) [8]. Also, if the applied torques are negligible. Then the right side of equations (10, 11, 12) (T_x, T_y, T_z) is approximately equal to zero, and (ω_z) is approximately constant. Then, equation (6) in form of components will be;

$$I_x\,\dot{\omega}_x + \left(I_z - I_y\right)\omega_y\omega_z = 0 \quad (13)$$

$$I_y\,\dot{\omega}_y + (I_x - I_z)\omega_x\omega_z = 0 \quad (14)$$

$$I_z\,\dot{\omega}_z + \left(I_y - I_x\right)\omega_x\omega_y = 0 \quad (15)$$

Taking the derivative of time of equation (13), then multiplying it by (I_y), and substituting the results in equation (14), gives

$$I_x I_y \frac{d^2\omega_x}{dt^2} = (I_y - I_z) I_y \frac{d\omega_y}{dt}\omega_z$$

$$= (I_y - I_z)(I_z - I_x){\omega_z}^2\omega_x \quad (16)$$

Now, if $\left(I_y - I_z\right)(I_z - I_x) < 0$, then (ω_x) will be bounded and have sinusoidal time dependence with frequency $\left(\sqrt{(I_y - I_z)(I_z - I_x)/I_x I_y}\,\omega_z\right)$, however, if $\left(I_y - I_z\right)(I_z - I_x) > 0$, then (ω_x) will increase exponentially. Thus, the motion is stable if (I_z) is either the largest or the smallest of the principal moments of inertia, and unstable if (I_z) is the intermediate moment of inertia. Equation (16) only establishes the stability over short time intervals; over long time intervals, energy dissipation effects cause rotational motion about the axis of smallest moment of inertia to be unstable [8].

4- Torque coils - (Design And Lows)

Magnetic coils used to generate magnetic dipole moment for attitude and angular momentum control. Also they are used to compensate for residual spacecraft biases and to make a correction to the attitude drift due to the disturbance torques.

When the current following through single loop, the torque coils will generate a magnetic dipole moment, according to equation (17) below

$$\vec{m} = \mu N\vec{I}A\hat{n} \qquad (17)$$

Where:

(μ) is the permeability of the core material.

($\hat{n}$) is a unit vector normal to the plane of the loop.

($\vec{I}$) is the current following through the loop of wire of the coils.

(A) is the area of the coil.

In TIGRISAT, The magnetic attitude control generated from a pair of coils fixed on each axis. These coils generate control torque perpendicular to the local Earth's magnetic field vector as it shown in **Fig. 4**, which varies with altitude and inclination of the orbit.

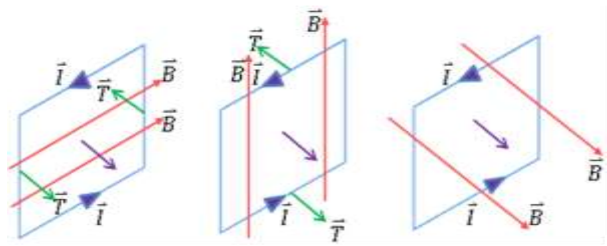


Fig.4 Intuitive torque coil operation

The magnetic field vector ($\vec{B}$) , shown in the **Fig.4** above, at the geometric center of the rectangular coil, with the length (a), and width (b) is given by the following equation

$$\vec{B} = \frac{2\mu NI\sqrt{a^2+b^2}}{\pi A}\hat{n} \qquad (18)$$

The interaction of this magnetic dipole moment ($\vec{m}$), with the Earth's magnetic field ($\vec{B}$) generates a torque ($\vec{T}$) according to the equation (19) beow

$$\vec{T} = \vec{m} \wedge \vec{B} \qquad (19)$$

Fig. 5.a TIGRISAT Top Coil

Fig. 5.b TIGRISAT Lower Coil

Fig. 5.c TIGRISAT Side Coil

Fig. 5 (a, b, c) TIGRISAT Torque Coils

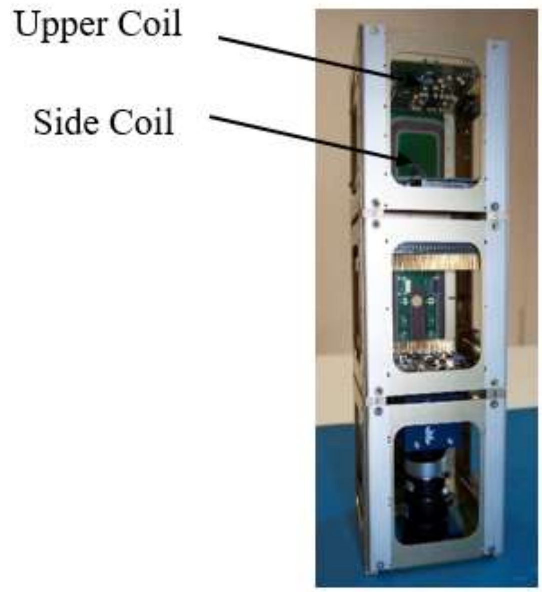


Fig.6 Tigrisat with Coils Assembled

The maximum current (I_{max}) and torque (T_{max}) calculated in TIGRISAT along the body axes shown below

$I_{max-x} = 0.174\ A$

$I_{max-y} = 0.0756\ A$

$I_{max-z} = 0.0504\ A$

$T_{max-x} = 0.0083$ N.m

$T_{max-y} = 0.0246$ N.m

$T_{max-z} = 0.0286$ N.m

when TIGRISAT separates from the launch vehicle, uncontrolled tumbling (uncontrolled motion) occur due to that separation. **Hence, the term tumbling refer to sizeable and undesired rotational velocities.** Detumbling could be accomplished by external means for example a remotely controlled robot or by impinging fluid jets on the uncontrolled spacecraft [12]. In fact, many schemes could be successful to detumbling the satellite. The algorithm that has been used in TIGRISAT to overcome the high values of the kinetic energy because of the high angular velocity induced by the launcher and by separation mechanism is B-dot algorithm. The proposed detumbling control represents a variation of the classical B-dot, in which the variable (m) is defined to be constantly orthogonal to earth magnetic field [10]. This approximation is reasonably accurate only if the angular rates are higher than the maximum rate of change of the geomagnetic field vector, equal to twice the orbital rate of the spacecraft [1]. The strategy is to use the B-dot damping term $(\vec{m}_{damp})$ in combination with a term that is proportional $(\vec{m}_{prop})$ to the misalignment angle between the radial direction $(\hat{r})$ and the body axis $(\hat{x}_b)$. Thus, the attitude pointing error can be obtained as follows

$$\text{pointing error} = \hat{r} \wedge \hat{x}_b$$

so that for perfect pointing $(\hat{r} \wedge \hat{x}_b = 0)$, if the opposite alignment is pursued $(\hat{x}_b = -\hat{r})$, it is enough to reverse the direction of dot product in pointing error formula. In real case and for good pointing this dot product should be almost equal to one.

$$\vec{m}_{damp} = -k_d \vec{B} \wedge \vec{\Omega} \quad (20)$$

$$\vec{m}_{prop} = -k_p \vec{B} \wedge (\hat{r} \wedge \hat{x}_b) \quad (21)$$

Where;

(k_d) is the damping gain.

Hence, the gains factors (k_d) and (k_p) can be defined by two diagonal matrices since the control is equally distributed on the two axes $(\hat{y}_b)$ and $(\hat{z}_b)$, whereas $(\hat{x}_b)$ of TIGRISAT is pointing the magnetic field. The two gains factors set to be (300000) for k_d and (100000) for k_p in the numerical calculations. These factors have been selected by inspection of the output results and there is no optimal criteria have been pursued. This value allows a satisfactory detumbling for all the scenarios considered and was set constant for the sake of simplicity, although an optimal value for the gain might be determined [3].

$(\vec{\boldsymbol{B}})$ is the earth magnetic field direction.

$(\vec{\boldsymbol{\Omega}})$ is the absolute angular velocity in the body frame.

Since the formula of the earth magnetic field also can be applied to find damping and proportional torques as it shown

$$\vec{T}_{damp} = \vec{m}_{damp} \wedge \vec{B} \quad (22)$$

$$\vec{T}_{prop} = \vec{m}_{prop} \wedge \vec{B} \quad (23)$$

It follow that the B-dot algorithm provides decreasing kinetic energy for any value of ($k_d > 0$) and it is appropriate for detumbling. In (TIGRISAT), its energy decrease until certain angular velocity, then the control strategy actuated to pursue a specified angular velocity whenever energy is decreased enough with respect to the inertial state. Theoretically, the detumbling limit achieved whenever the spacecraft rotation becomes equal to the geomagnetic field rate.

5- Simulation

Starting from the mass of TIGRISAT, which (4kg), and the inertial tensor is diagonal $[6.667 * 10^{-3}, 0.0333, 0.0333] kg.m^2$. The nominal output of the torque coils is [0.167 0.246 0.164] $A.m^2$ with an initial relative angular velocities equal to [5 0.2 3] deg./s. Then, the simulation results are listed as follows

a. Absolute Euler Angles

Fig.7 show that the absolute Euler angles (Phi, Theta, Psi) which are the angles between the Earth fixed frame ($\hat{c}_1, \hat{c}_2, \hat{c}_3$) with the body reference frame of the TIGRISAT ($\hat{x}_b, \hat{y}_b, \hat{z}_b$), start in high oscillating, then after ($60000\ sec$) which is about ($16.66\ hr$) it takes a uniform behavior. The high variation at the beginning belong to the high kinetic energy of the satellite due to the ejection from the launch vehicle, this kinetic energy will be dissipated during the time.

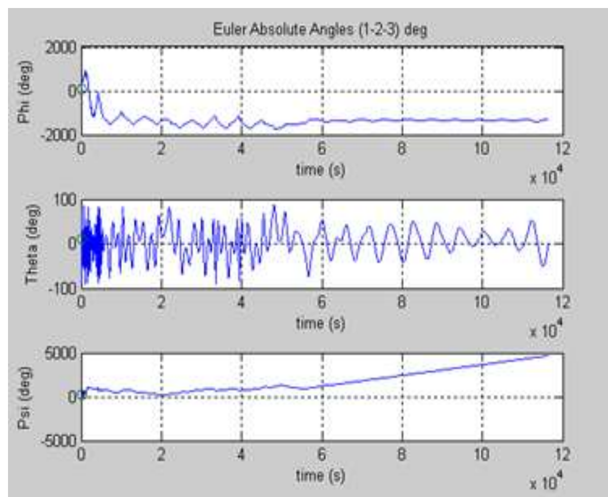


Fig. 7 Absolute Euler angles

b. Euler Absolute Angular Velocities

Fig. 8 show that the Euler absolute angular velocities still oscillating along ($5710\ sec$) with respect to angular velocity (P), ($5500\ sec$) with respect to the angular velocity (Q), and about

($5400\ sec$) with respect to the angular velocity (R) the curve plotted corresponding to the nutation and the procession angles (1-2-3). When the attitude has been controlled, the two angles would be controlled near to zero and becomes steadier.

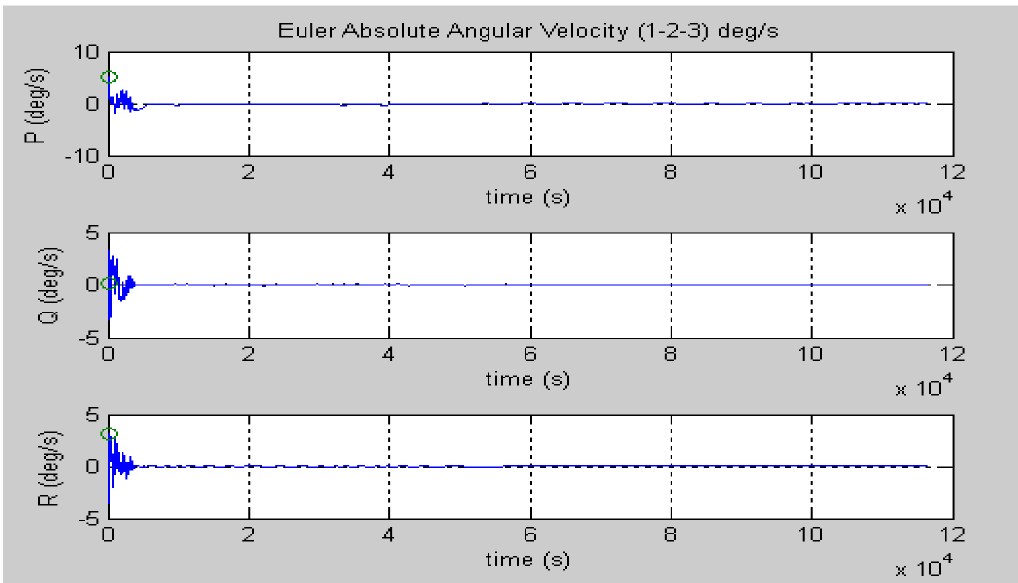


Fig. 8 Absolute Euler Angular Velocities

c. Relative Euler Angles

The relative Euler angles represents the angles between the orbital frame $(\hat{r}, \hat{\theta}, \hat{h})$ and the body frame $(\hat{x}_b, \hat{y}_b, \hat{z}_b)$ of the spacecraft. The angle (Phi) in **Fig.9** rotates about (176°) per the first nine orbital periods, then this rotation will decrease until it reaches the minimum value which is about (12°) after eighteen period.

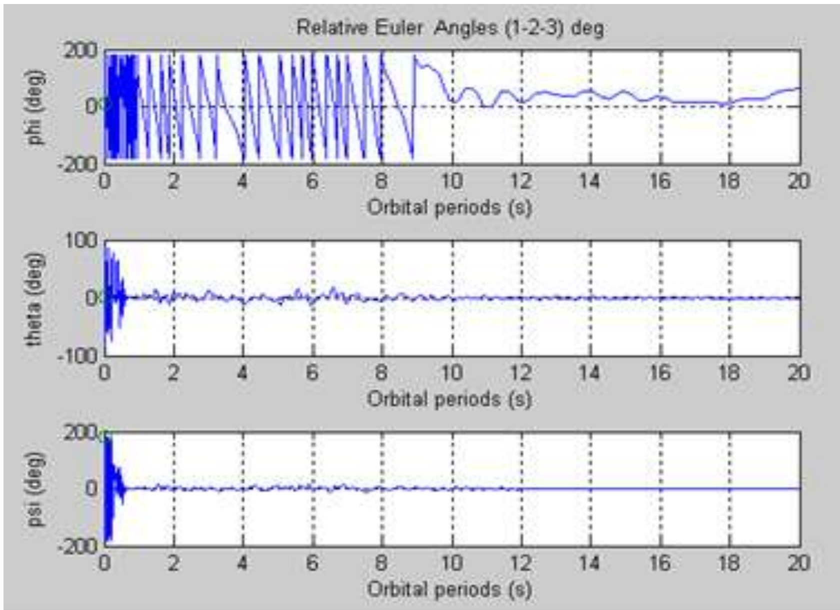


Fig. 9 Relative Euler angles

Hence, the angle (Phi) represents the rotation of the body axis ($\hat{x}_b$) of TIGRISAT, while this axis functioned to point the Earth (Nadir pointing), where the camera is fixed on this axis. This result consider acceptable, because the rotation of this angle will be very slow, then, it will not effect on the camera resolution after (10 periods) for variety of missions, maintaining a residual spin of rotation could be desirable [14].

d. Euler Relative Angular Velocity

The relative angular velocity would be damped after (5700 sec) below (0.4

deg). Where, (p), (q), (r) refer to (w_x), (w_y) and (w_z) respectively.

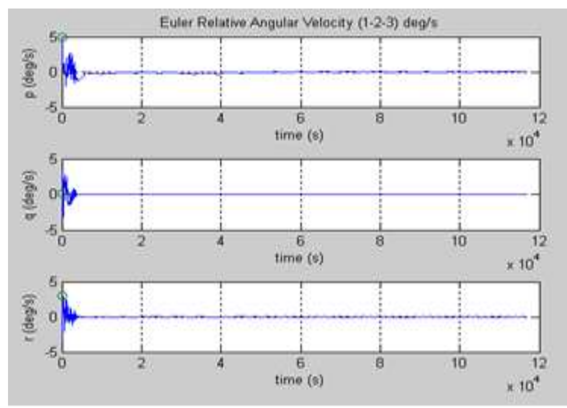


Fig.10 Relative angular velocities

Hence, Angular rate measurements can be particularly useful for missions in which deferent control on the three axes is required; this is for instance the case of Y-Thompson spin [20], 21].

e. Kinetic Energy

The plot of the kinetic energy of the TIGRISAT shows that, the maximum value is about $(8.353 * 10^{-5})$. Then it decreases rapidly along $(5700\, sec)$ which about (1.58 hr). This time considered a turning point, because the kinetic energy will dissipate until it reaches zero.

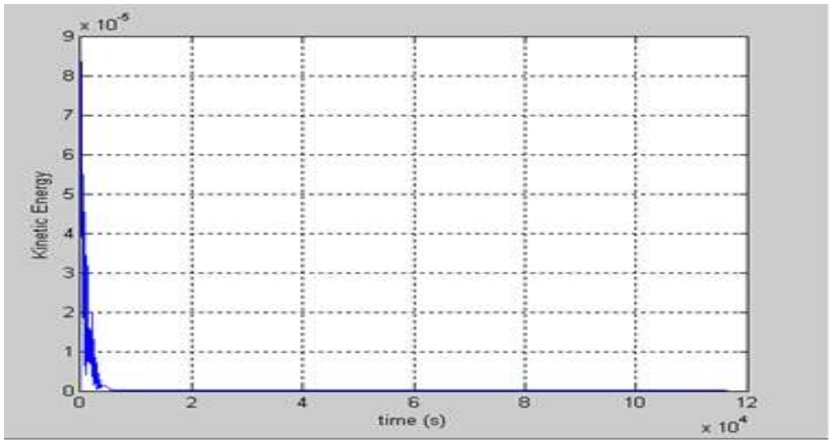


Fig.11 The Kinetic energy

f. Satellite Magnetic Dipole

Fig.12 shows that the magnetic dipole components at each axis of the TIGRISAT's body reference frame

$(\hat{x}_b, \hat{y}_b, \hat{z}_b)$. The maximum values of the magnetic dipole set to be $(0.2\ Ampere.m^2)$. In fact, this value is needed just at the very beginning, which about $(30000\, sec)$ with respect to the body axis $(\hat{x}_b)$, $(60000\, sec)$ with respect to the body axis $(\hat{y}_b)$, and about $(50000\, sec)$ with respect to the body axis $(\hat{z}_b)$. Then, after $(80000\, sec)$ the value $(0.1\ Ampere.m^2)$ of the magnetic dipole is enough to stabilize TIGRISAT later.

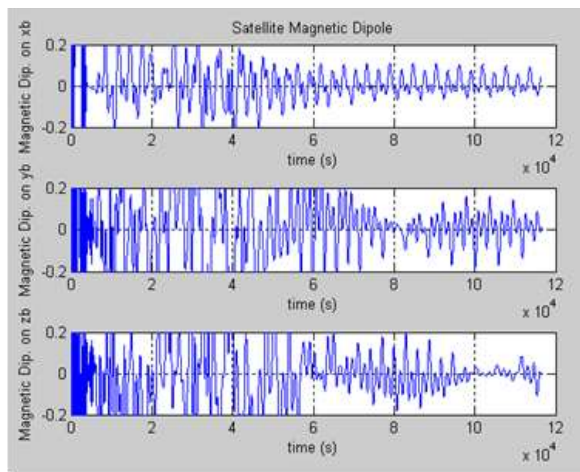


Fig.12 Satellite magnetic dipole

g. Current Distribution

Fig.13 shows that the current needed for each axis in the body reference frame of TIGRISAT $(\hat{x}_b, \hat{y}_b, \hat{z}_b)$. The maximum value of the current appeared at $(\hat{x}_b)$ axis, which is about

($0.08\ A$) in the first ($40000\ sec$), then this value decrease until it reaches less than ($0.04\ A$) over time.

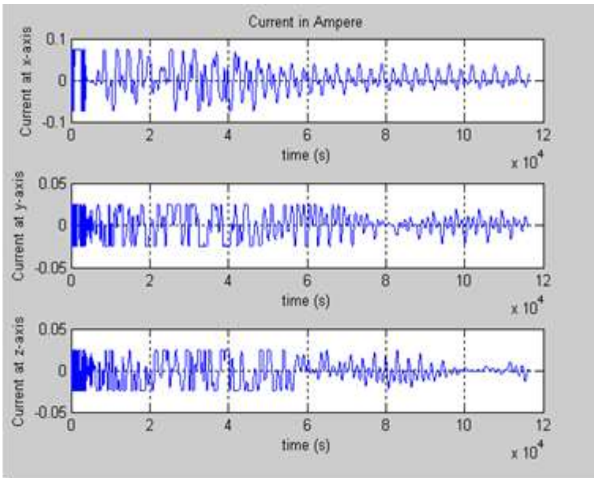


Fig.13 Current components

h. Power Distribution

Fig.14 show the power values at each axis of the body reference frame of TIGRISAT. The maximum power value can be noticed at $\hat{x}_b$-axis that is equal to ($0.25\ Watt$) during the first ($40000\ sec$) then it becomes ($0.06\ Watt$) after ($10000\ sec$). While the body axis ($\hat{y}_b$), shows ($0.08\ Watt$) during the first ($70000\ sec$). Then the body axis ($\hat{z}_b$) needs ($0.08\ Watt$) during the first ($50000\ sec$) then it decreases with time.

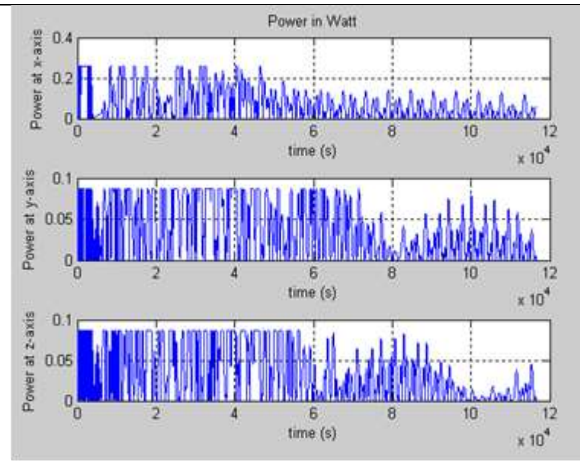


Fig.14 Power consumption

Finally, **Fig.13** below shows clearly that the total power consumption

decrease from ($0.432\ Watt$) to ($0.143 Watt$) after ($118000\ Sec$).

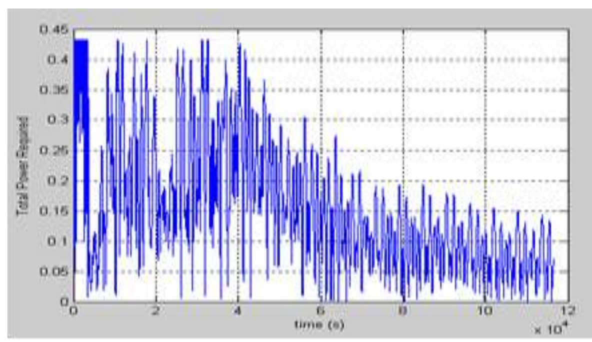
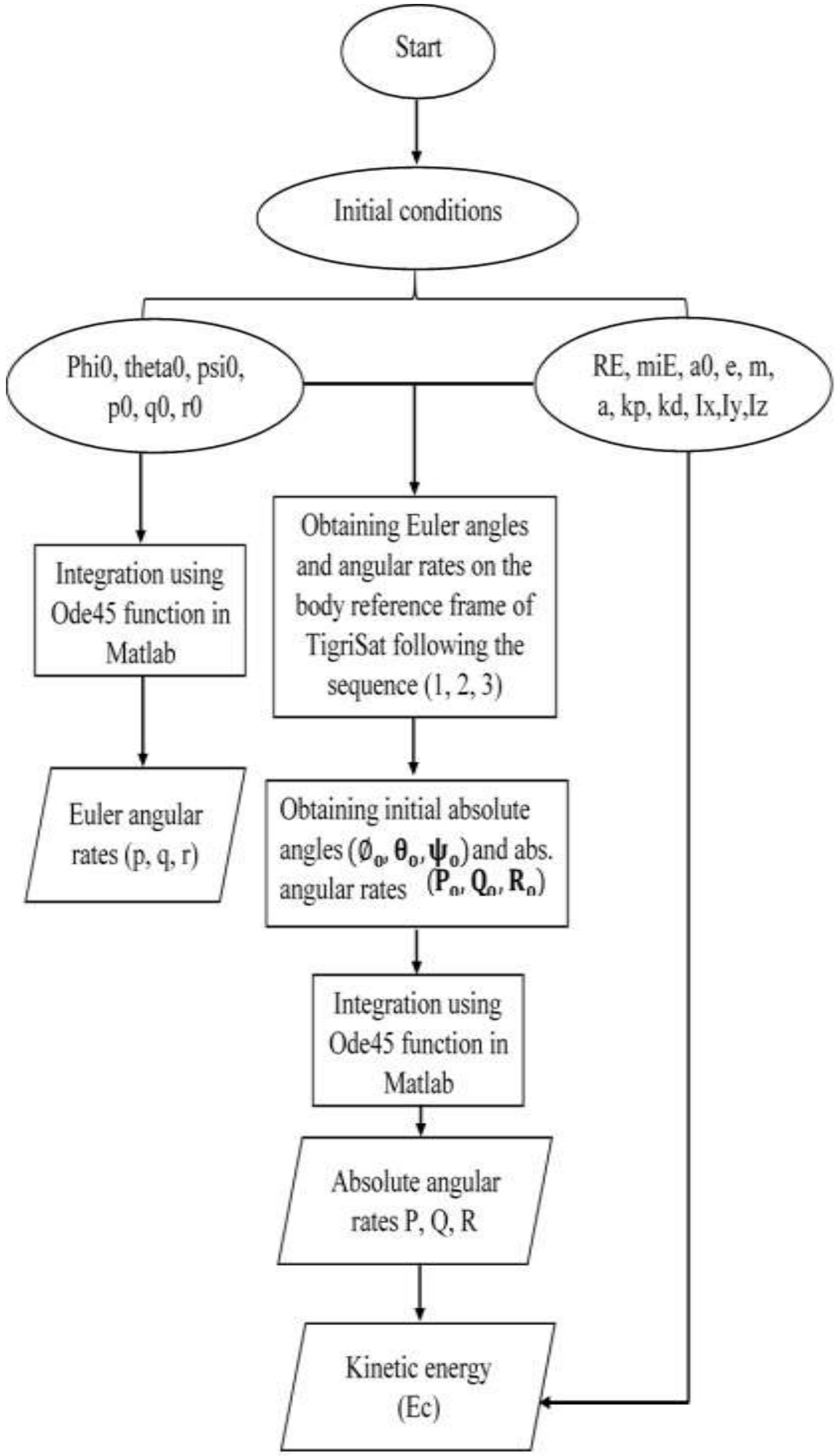
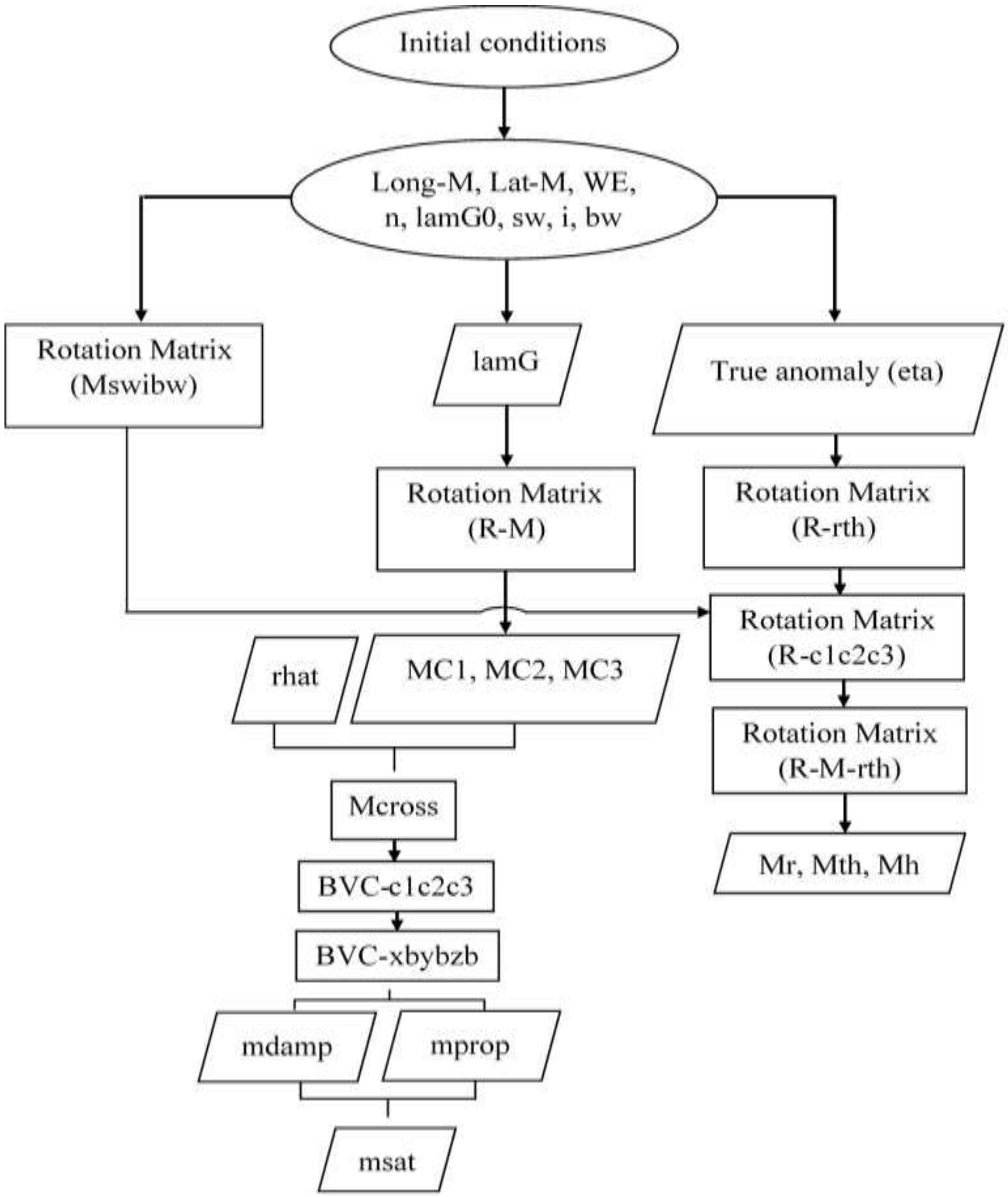


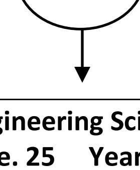
Fig. 15 Total Power consumption

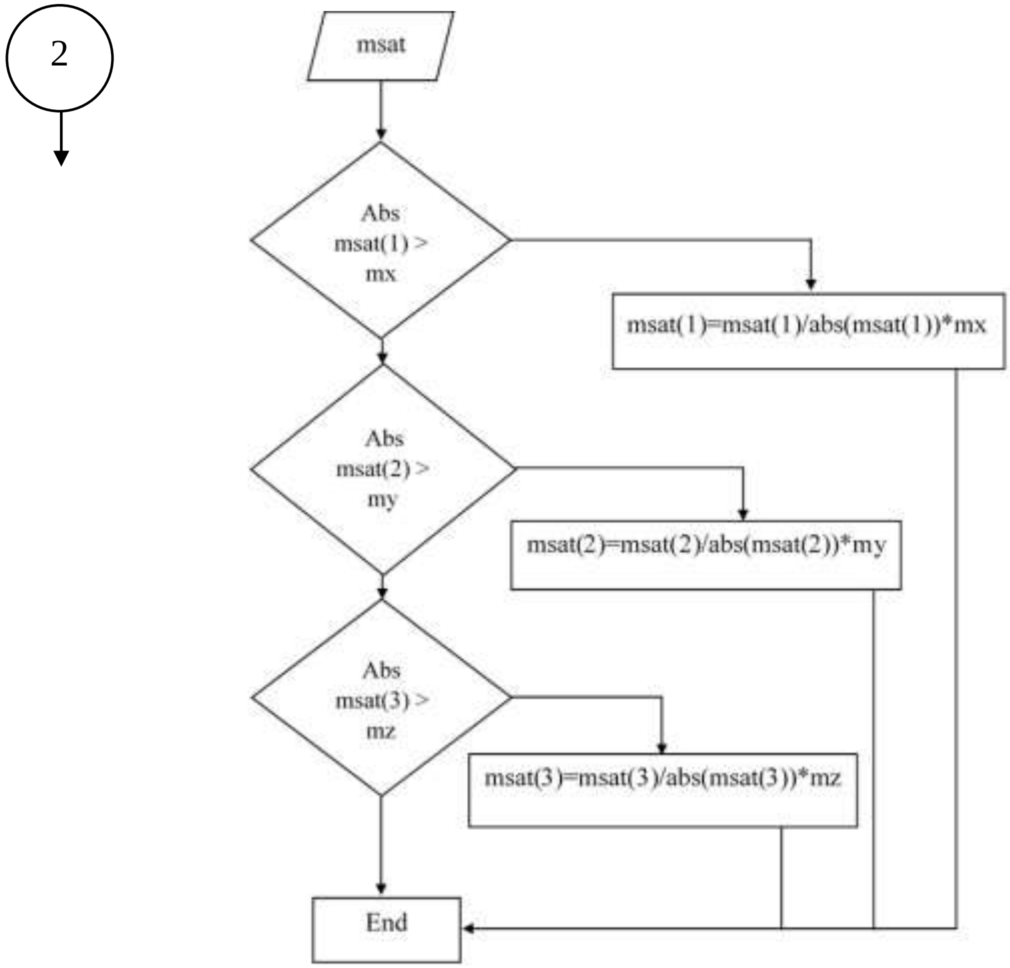
All the previous results are obtained according to the flowchart below;


Start
Initial conditions
Phi0, theta0, psi0, p0, q0, r0
RE, miE, a0, e, m, a, kp, kd, Ix,Iy,Iz
Integration using Ode45 function in Matlab
Euler angular rates (p, q, r)
Obtaining Euler angles and angular rates on the body reference frame of TigriSat following the sequence (1, 2, 3)
Obtaining initial absolute angles ($\emptyset_0, \theta_0, \psi_0$) and abs. angular rates (P_0, Q_0, R_0)
Integration using Ode45 function in Matlab
Absolute angular rates P, Q, R
Kinetic energy (Ec)

The sub-routine file (UEMagnfield3)







6- Conclusion

The simulation of the attitude control using three magnetic coils in TIGRISAT appears a good results, especially when a low cost control have been used (Torque Coils). The algorithm is also suitable for yielding three-axis stabilization of a CubeSat deployed in low earth orbit (LEO). The simulation proved that TIGRISAT would damp after less than two orbital periods. **Hence, TIGRISAT orbital period is equal to 1.611 hr,** taking into account that the maximum dipole moment fixed to ($0.3Am^2$). In real time, angular rates can be determined based on three- axis torque coils measurements. Nadir pointing will be provided with (12 deg.) in less than 10 periods and that is mean the first picture could be get in the first life day of TIGRISAT. Eventually, the simulation provide a convenient condition to test the attitude control of

TIGRISAT from detumbling to stabilization state then to get the desired pointing considerable reduction in the cost and electrical power consumption.

Nomenclature

RE: Earth radius in (Km).

miE: Earth gravitational constant.

a0: Semi-major axis of the circular orbit in (Km).

e: Eccentricity of the orbit.

m: The mass of the satellite.

a: Width dimension in (m).

b: Length dimension in (m).

L: height dimension in (m).

phi0, theta0, psi0: Initial relative angles.

p0, q0, r0: Initial relative angular rates.

kp, kd: Proportional and damping terms.

Ix, Iy, Iz: Moment of inertia of the satellite.

Long_M: Geographic longitude west of Greenwich (-69).

Lat_M: Geographic latitude (78.5).

LamG0: Initial Greenwich latitude.

tau: Time of the (Ode45) integration function.

R_M: Rotation matrix that relates the Earth fixed frame (C1, C2, C3) with the Earth magnetic field components.

Mc1, Mc2, Mc3: The components of the Earth magnetic field on the Earth fixed frame (C1, C2, C3).

bw, i, sw: The angles of the selected orbit to eject the satellite in it.

eta: The true anomaly, also called Theta Star (θ^*).

R_rth: Rotation matrix that relates $(\hat{e}, \hat{p}, \hat{h})$ frame to $(\hat{r}, \hat{\theta}, \hat{h})$ frame.

R_C1C2C3: Rotation matrix that relates $(\hat{C}1, \hat{C}2, \hat{C}3)$ frame to $(\hat{r}, \hat{\theta}, \hat{h})$ frame.

R_M_rth: Rotation matrix that reads the Earth magnetic field components in the orbital frame $(\hat{r}, \hat{\theta}, \hat{h})$.

Mr, Mth, Mh: The components of the Earth magnetic field in the orbital frame $(\hat{r}, \hat{\theta}, \hat{h})$.

etap: Modulus of the orbital velocity which is equal to $\sqrt{\frac{miE}{a^3}}$.

EMF_C1C2C3: The vector of the Earth magnetic field $(\hat{C}1, \hat{C}2, \hat{C}3)$ frame.

Mcross: A matrix that relates the radius versor of the satellite with the Earth magnetic field $(\hat{C}1, \hat{C}2, \hat{C}3)$ frame.

Bvc_xbybzb: A matrix that gives the magnetic field value experienced by the satellite.

mdamp: Damping term produced by the coils.

mprop: Proportional term

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التحليل النظري والعددي لنظام التوجيه والتحكم لقمر صناعي ثلاثي الوحدات – القمر العراقي (TIGRISAT)

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الخلاصة: -

TIGRISAT، هو قمر صناعي صغير متكون من ثلاثة وحدات مكعبة، حددت له مهمة مراقبة الغبار، ونتيجة لذلك استخدمت طريقة التوجيه العمودي على الأرض لتحقيق هذا الغرض. ان نظام السيطرة وتحديد التوجيه يجب أن يكون قادر على التحكم بزوايا التوجيه الثلاثة للقمر وهي $(\emptyset)$ و (θ) و (ψ) على التوالي. تنويه، استخدمت طريقة التوجيه العمودي على محور (x) للقمر حيث مكان تثبيت الكاميرا والزاوية $(\emptyset)$ هي من تتحكم بهذا المحور. بما أن TIGRISAT هو قمر صناعي صغير وقليل الوزن $(4\ kg)$، استخدمت فيه طريقة الملفات الكهربائية لتوليد العزم اللازم لتوجيه القمر والسيطرة على الزخم الزاوي. كما تستخدم هذه الطريقة لتعويض انحراف القمر الناتج عن عزوم الاضطراب البيئية. زوج من الملفات أستخدمت للسيطرة على كل محور من محاور القمر، عدد لفات الملف الجانبي (220 لفة) وعدد لفات الملف العلوي والسفلي (320 لفة). أعظم قيمة عزم تنتجه هذه الملفات هو (0.0386 N.m) وهذه القيمة كافية للتغلب على عزوم الاضطراب البيئية ولتوجيه القمر بالاتجاه المطلوب. كذلك صممت خوارزمية لمعرفة العزم الناتج والذي يكون متعامد بأستمرار على متجه الفيض المغناطيسي الأرضي. الخوارزمية المصممة يعطي قيمة التيار المطلوب لاستقرار كل محمور من محتور القمر، فضلا عن القدرة المستهلكة والطاقة الحركية والنسب الزاوية.

الكلمات المفتاحية: - TIGRISAT، القمر المكعب، التوجيه العمودي، ملفات العزم، اللوغاريتم B-dot.