Agile Maneuvers for Near Earth Object (NEO) Fly-by Missions

Vaios Lappas¹, Bong Wie² and Jozef van der Ha³

¹ Surrey Space Centre, University of Surrey, GU2 7XH, United Kingdom, E-mail: v.lappas@surrey.ac.uk
² Arizona State University, Tempe, AZ 85287-6106, USA, E-mail: bong.wie@asusat.edu
³ Consultant, 10001 Windstream Drive, Columbia, MD, USA, E-mail: JvdHa@aol.com

Abstract

Small Satellites are establishing themselves as important tools for exploring our solar system. Developments in micro-electronics have enabled small and low-cost deep space probes to complement conventional space platforms in long-duration deep space missions. The paper presents a baseline design of an attitude control system for a spacecraft performing a Near Earth Object (NEO) fly-by mission. Following the autonomous escape and cruise phases, the NEO encounter phase is the most critical mission phase with the attitude control performed by a cluster of small Control Moment Gyros (CMG’s). The satellite needs to be rotated relatively fast to keep the NEO within its field of view for the imaging of the NEO. Simulations demonstrate the practicality and versatility on the use of CMGs for low-cost NEO deep space missions.

Introduction

It is known that Near Earth Objects (NEO’s) pose a potentially catastrophic danger for earth. Thus there is a need to better understand NEO’s and to better predict their orbits. Low-cost deep space probes can be useful and cost-effective for gathering information on NEO’s. A mini-satellite mission that is capable of supporting a 10-kg science payload will be presented here. The main mission objective is to demonstrate the capability to intercept a NEO in deep space and to perform surface imaging. Surrey Satellite Technology Ltd. (SSTL) has a proven track record of successful low-cost satellite missions and has ambitions to demonstrate the same cost-effective design philosophies for deep space applications [1, 2]. The conceptual platform design assumed in the present study is basically identical to the one resulting from a previous SSTL system design study for an ‘entry level’ NEO mission [3]. The present paper focuses on the design of the Attitude Determination and Control System (ADCS) for a low-cost SSTL-built mini-satellite performing a NEO flyby. The proposed concepts are illustrated using the example of a low-cost mini-satellite that performs an imaging mission to NEO 4179 Toutatis shown in Fig. 1. The low-cost nature of the mission dictates that, during the fast fly-by phase, the satellite must execute a fast rotation about its pitch axis in order to be able to keep its imager pointing at the target object.

The proposed ADCS design uses small agile Control Moment Gyro (CMG) actuators and low-cost attitude sensors. The Micro-CMG’s provide the fast spacecraft rotation rate (up to 6 deg/sec) that is needed to perform the NEO imaging during the critical encounter phase.

2. Mission Analysis

2.1 Selected NEO Target

On the basis of the results of previous studies [3, 5] performed at the Surrey Space Centre, a single suitable candidate NEO was selected for the present study: 4179 Toutatis (Fig. 1) which is relatively large and a potential ‘contact binary’. It came within a scant 1.5 million kilometers of the earth on 29 September 2004 and will approach earth again in 2008. The Toutatis object is of interest because it achieves one of the closest earth approaches of any known asteroid or comet between now and 2060, and the approach occurs in the near term.
2.2 Trajectory

There are a number of potential low-cost launch opportunities, but the lowest cost launch is most likely offered by the PROTON rocket, which provides a secondary payload capability of about 400 kg into a geo-stationary orbit. When starting from this relatively attractive orbit, earth escape can be achieved at a cost of about 1300 m/sec. The encounter with 4179 Toutatis in 1998 would require an additional 200 m/sec [3]. The proposed NEO2M (NEO Mini-satellite Mission) trajectory consists of three parts: (i) the 267-days escape phase, when the satellite escapes from the earth’s sphere of influence starting from its initial geostationary orbit; (ii) the 134-days approach phase when the spacecraft cruises to the NEO Toutatis; (iii) the short encounter phase when it conducts the actual NEO flyby. During the escape phase the semi-major axis is increased by means of relatively short perigee kicks. At the time of earth approach, Toutatis is near its perihelion and has a speed of about 40 km/s. The relative speed of the mini-satellite and Toutatis at encounter is close to 10 km/sec.

2.3 Imaging

Currently, existing Toutatis imagery is limited to radar data at relatively low resolution (Fig. 1), collected at JPL’s Goldstone site. The collection of optical imagery would indisputably be a crucial objective of the Toutatis mission. The availability of 10-meter or better optical images would greatly increase our knowledge of this particular NEO and would improve our understanding of its complicated dynamics and structure. The NEO2M satellite will have two imagers: the Wide Field Of View (WFOV) and the Narrow Field Of View (NFOV) cameras. The WFOV imager has a 20° by 20° field of view and allows target acquisition from about 250,000 km away at 7 hours before closest approach. The WFOV camera produces wide-angle NEO images and provides inputs for optical navigation. The proposed NFOV camera is a miniaturized micro-imager derived from the SMART-1 camera. It has a 4° x 4° field of view, a 1024 x 1024 detector array, and a 120 mm main lens for capturing large NEO surface features. The NFOV imager is capable of acquiring about 40 seconds worth of high-resolution images at a rate of 30 frames per second. A more manageable concept (from a low-cost design point of view) may be based on five NFOV frames per second for a total of 200 images. The NFOV camera should be capable of achieving a GSD resolution of less than 10 meter around the time of closest approach with Toutatis (with length of 6.5 km) almost completely filling the imager’s field of view. Although it may well be feasible to enhance the present capabilities of the NFOV micro-imager by using higher-resolution detector arrays, only the existing design is considered in the present paper. The 4° field of view leads to a GSD resolution of 6.8 m per pixel at the minimum miss distance of 100 km. On the basis of this design baseline, we find that NEO Toutatis fills less than 2% of the total image at the time when the probe is 5000 km away from the object. When we assume a worst-case system-level pointing capability of about 0.1 deg, we see that this corresponds roughly to the size of Toutatis at a 5000 km distance. At closest approach, the assumed pointing error amounts to about 175 m or less than 3 % of the NEO size. It can be expected that, at the subsystem level, the largest part of the total pointing error budget can be allocated to the ADCS design. In terms of pointing stability requirements, simulations indicate that $3 \times 10^{-3}$ deg/sec would be sufficient for the present mission objectives.

2.4 Required Tracking Rate

Fig. 2 shows the (planar) encounter geometry of the probe relative to the NEO near the time $t_{CA}$ of closest approach. $D$ denotes the miss distance at the time $t_{CA}$ and $R(t) = V(t - t_{CA})$ represents the varying distance between the probe and the NEO as a function of time. $V$ is the relative flyby velocity which may be assumed to remain constant over the short interval of time under consideration. The required probe’s pitch rotation angle equals the NEO aspect angle $\alpha(t)$ as shown in Fig. 2. In order to ensure that the camera keeps pointing towards the NEO during the encounter phase, the pitch angle profile that must be tracked by the ADCS is:

$$\alpha(t) = \arctan \left( \frac{D}{R(t)} \right)$$  \hspace{1cm} (1)

Fig. 3 shows the evolution of $\alpha(t)$ near the time of closest

Figure 1: Radar Image of 4179 Toutatis [4]}
Figure 2: NEO Encounter Geometry

Figure 3: Toutatis Aspect Angle: $\alpha(t)$
approach. The expression for the rate of change of the pitch angle $\alpha(t)$ follows from eq. 1:

$$\frac{d\alpha}{dt} = \frac{VD}{(D^2 + V^2)} \quad (2)$$

Fig. 4 shows its behavior near the time $t_{CA}$. On the basis of the adopted values for the flyby velocity $V = 10$ km/s and the minimum miss distance $D_{min} = 100$ km, we find that the maximum required pitch rate (at the time of closest approach) equals $5.7^\circ$/sec. This result forms the basis for the sizing of the CMG control capability.

3. Spacecraft Design

The NEO2M Mini-satellite platform will be derived from Surrey’s existing spacecraft configurations [1, 2, 3]. Its diameter is 1.4 m and its height is 0.8 m. The thrust tube is made of 2 mm thickness aluminum alloy sheet and is capable of supporting an additional spacecraft mounted on top for a dual launch. The preliminary mass budget for a spacecraft design with a 10-kg science reference payload is provided in Table 1. The satellite moments of inertia are estimated to be $[I_{xx}, I_{yy}, I_{zz}] = [53, 53, 60]$ kg m$^2$.

4. ADCS Architecture

4.1 Selection of Actuators

The objective of the ADCS is to support the mission during all its phases. Of particular importance is the implementation of the high rotation rate required for the NEO imaging around the time of closest approach. For achieving the required spacecraft pitch rate, there are at least three design options: (i) using a dedicated rotating scan mirror similar to the design implemented for the CONTOUR probe [6]; (ii) using thrusters as actuators; and (iii) employing a Micro-CMG cluster as actuators. Option (i) presents a potential single point failure (without a fall-back option) resulting in loss of mission. Option (ii) would become extremely complex in view of the intricate time dependency of the rate history. Option (iii) has the CMG’s tracking the asteroid in a more mass-and power-efficient way than the thrusters could do. Even if one of the gyro failures, a 3-CMG system will still be able to track the NEO, although with a degraded performance. Furthermore, there may still be a third level of redundancy by using a combination of CMG’s and thrusters. Therefore, a CMG-based ADCS system will provide an efficient and redundant means of tracking the NEO around close approach. Finally, it may be noted that the use of CMG’s offers a substantial amount of flexibility in the case of a mission extension with additional flybys of other candidate NEO’s. Following a detailed trade-off of a number of sensor combinations, the baseline ADCS suite shown in Table 1 has been selected. Table 2 presents a summary of the mass characteristics of the NEO2M Minisatellite platform.

5. Attitude Control by Micro-CMGs

The most critical ADCS control objective of the mission occurs around the time of closest approach with the NEO object. The spacecraft must be rotated about its pitch axis with a rate of close to $6^\circ$/sec in order that the imager keeps pointing towards the NEO. The evolution of the pitch angle and rate as a function of time are shown in Figs. 3 and 4 and form the basis for the design of the CMG control law implementation. Micro-CMG’s are the baseline actuators for performing the three-axis attitude control because of their low-mass and low-power properties and agility. Surrey Satellite Technology Ltd. (SSTL) has considerable in-flight experience with these CMG’s [6] so the risk of using this hardware on a NEO flyby mission is acceptable. Table 3 summarizes the design characteristics of the proposed SSTL Micro-CMG’s and Fig. 5 provides a visualization of the CMG elements.

The maximum attitude control torque that needs to be delivered by the CMG’s must be determined on the basis of the maximum required spacecraft rotation rate of $6^\circ$/sec, the spacecraft spin axis moment of inertia of about $60$ kg m$^2$ and the interval of time allowed to achieve the maximum rotation rate (taken as 3 sec). The required angular momentum $h_0$ per CMG for a 4-CMG cluster in a skewed pyramid configuration can be calculated as:

$$h_0 = \frac{1}{2} H/(1 + \cos \beta) \approx 0.317H \quad (3)$$

where $H$ stands for the total angular momentum of the CMG cluster and $\beta = 54.7^\circ$ is the skew angle. Finally, the gimbal rate for the control execution must be calculated from the applied torque and $h_0$.

From previous SSTL’s CMG experience [6] it appears feasible that the required angular momentum of 1.99 Nm s can be achieved with a gimbal rate of about $85^\circ$/s. In order to achieve the CMG angular momentum $h_0$, a flywheel with angular speed $\omega_w = 6000$ rpm and a spin moment of inertia of 0.0032 kg m$^2$ has been selected based on SSTL’s experience with reaction/momentum wheels and Micro-CMG’s.

For the ADCS systems, if we use a bandwidth of 0.5 Hz (typical for Surrey Satellites) the bandwidth of the gimbal motor dynamics should be at least 10 times higher at 5 Hz (i.e., accelerate to the maximum gimbal rate of 1.5 rad/s in 0.2-0.5s). For a gimbal rate of 1.5 rad/s with a 33.3% performance margin backup (i.e. 2 rad/s) the gimbal acceleration to be provided from the gimbal motor will result to an acceleration of 10 rad/s$^2$. From this and if we assume (preliminary assumption) that the inertia of the gimbal motor will be dominated by the flywheel MOI:

$$N_g = I_g \delta_{max} \quad (4)$$
Table 1: NEO2M Platform Characteristics

<table>
<thead>
<tr>
<th>Component</th>
<th>Units</th>
<th>Mass (kg)</th>
<th>Power (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Micro-CMG’s</td>
<td>4</td>
<td>2.5</td>
<td>10</td>
</tr>
<tr>
<td>V-Slit Sun Sensor</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>3-axis Sun Sensor</td>
<td>1</td>
<td>0.3</td>
<td>0.1</td>
</tr>
<tr>
<td>BAE Gyros</td>
<td>4</td>
<td>0.035</td>
<td>0.25</td>
</tr>
<tr>
<td>Star Camera</td>
<td>2</td>
<td>1.7</td>
<td>2.8</td>
</tr>
<tr>
<td>Thrusters</td>
<td>8</td>
<td>0.28</td>
<td>10</td>
</tr>
<tr>
<td>Margin (20%)</td>
<td></td>
<td>3.4</td>
<td>10</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>&lt; 20</strong></td>
<td><strong>&lt; 150</strong></td>
</tr>
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</table>

Table 2: ADCS Mass and Power Budgets

<table>
<thead>
<tr>
<th>Subsystems</th>
<th>Mass (kg)</th>
</tr>
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<tbody>
<tr>
<td>Payload</td>
<td>10.0</td>
</tr>
<tr>
<td>Propulsion</td>
<td>208.5</td>
</tr>
<tr>
<td>Structure (includes harness and solar arrays)</td>
<td>54.3</td>
</tr>
<tr>
<td>Attitude Determination and Control</td>
<td>19.5</td>
</tr>
<tr>
<td>Power</td>
<td>16.2</td>
</tr>
<tr>
<td>Communications</td>
<td>11.6</td>
</tr>
<tr>
<td>Environment (radiation and thermal)</td>
<td>7.1</td>
</tr>
<tr>
<td>On Board Data Handling</td>
<td>2.8</td>
</tr>
<tr>
<td><strong>Margin (20 %)</strong></td>
<td>31.3</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td>396</td>
</tr>
</tbody>
</table>

Table 3: Specifications of SSTL Micro-CMG’s

<table>
<thead>
<tr>
<th>Specifications of SSTL Micro-CMG’s</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Satellite MOI</td>
<td>(53, 53, 60) kg – m²</td>
</tr>
<tr>
<td>Maximum Slew Rate $\omega_{max}$</td>
<td>6 °/sec</td>
</tr>
<tr>
<td>CMG Cluster Skew Angle $\beta$</td>
<td>54.7 °</td>
</tr>
<tr>
<td>Total Angular Momentum $H$</td>
<td>6.28 Nms</td>
</tr>
<tr>
<td>CMG Angular Momentum $h_0$</td>
<td>1.99 Nms</td>
</tr>
<tr>
<td>Torque $N_{CMG}$</td>
<td>2.0944 Nm</td>
</tr>
<tr>
<td>Gimbal Rate</td>
<td>1.315 rad/sec</td>
</tr>
<tr>
<td>CMG Flywheel Inertia Moment</td>
<td>0.00235 kg – m²</td>
</tr>
<tr>
<td>Flywheel Speed $\omega_w$</td>
<td>6000 rpm</td>
</tr>
</tbody>
</table>
Figure 5: Conceptual Micro-CMG Design

Figure 6: Conceptual Micro-CMG Design
Figure 7: Conceptual Micro-CMG Design

Figure 8: Conceptual Micro-CMG Design
For a gimbal MOI \( I_g = 0.004 \text{kg} \cdot \text{m}^2 \) and a gimbal acceleration of 10 rad/s\(^2\), \( N_g = 40 \text{ mN-m (or } 4 \times 10^{-2} \text{ Nm)\. Thus the torque amplification factor for the CMG would be:}

The torque amplification factor is similar to that of other CMG units available.

### 5.1 Agile Maneuvers with CMGs

The following simulations use the Generalised Singularity Robust singularity avoidance logic [7, 8]. The CMG sizing specifications have given a design specification for a 4-CMG cluster (Table 3). A simulation for the required NEO tracking maneuver is provided in Figures 6. The PID logic and singularity avoidance scheme used in the NEO tracking maneuver have been presented in detail in Wie [7, 8]. In summary:

\[
\tau = -J \left\{ 2k \frac{sat}{L_i} \left( e + \frac{1}{T} \int e \right) + \omega \right\}
\]

\[
L_i = \frac{c}{2k} \min \left\{ \sqrt{4a_i |e_i| \omega_{i_{\text{max}}}} \right\}
\]

\[
\delta = A^\# h
\]

\[
A^\# = A^T \left[ AA^T + \lambda E \right]^{-1}
\]

\[
u = -\tau - \omega \times h
\]

where,

\[
E = \begin{bmatrix} 1 & \epsilon_3 & \epsilon_2 \\ \epsilon_3 & 1 & \epsilon_1 \\ \epsilon_2 & \epsilon_1 & 1 \end{bmatrix} > 0
\]  

\(\lambda\) is a scalar

\(\epsilon_i\) is selected as a modulation function: \(\epsilon_i = \epsilon_0 \sin(\omega t + \phi_i)\)

\(\epsilon_0\) is the amplitude

\(\omega\) is the modulation frequency

\(\phi_i\) is the modulation phase offset

The results show that the proposed CMG’s are capable of performing the required maneuver with a comfortable margin and without exceptionally large excursions of the gimbal angle.

### 6. Conclusions

A preliminary design of an autonomous guidance and control system for a mini-satellite performing a Near Earth Object (NEO) fly-by mission has been proposed. After the transition from spin to three-axis mode, the attitude knowledge is provided by a set of low-cost gyroscopes in combination with a star sensor. For the execution of the tracking control during the critical encounter phase, a Micro-CMG cluster has been selected and its specifications have been determined. The CMG’s performance has been assessed by means of realistic simulations. The CMG’s prove to be an efficient means of providing the agility required to track the NEO for the imaging. The results demonstrate the practicality and versatility of the proposed guidance and control concept for low-cost NEO deep space missions.

### Bibliography


