ATTITUDE CONTROL ACTUATORS, SENSORS AND ALGORITHMS FOR A SOLAR SAIL CUBESAT

Prof W.H. Steyn
University of Stellenbosch, South Africa, whsteyn@sun.ac.za

The paper describes the development of the full ADCS subsystem for a small 3U Cubesat solar sail mission. The various new control and estimation algorithms, actuators and sensors designed for this mission will be presented. The Cubesail mission will deploy a 5 by 5 meter solar sail from at least a 750 km circular polar low earth orbit (LEO) to limit the effect of aerodynamic drag and maximise the influence of solar radiation pressure on the deployed sail. This proof of concept will demonstrate an two degree change in the orbit inclination over a period of less than a year due to solar sailing. The mission aim will therefore be to validate existing solar radiation pressure models. A future application of this technology will be to use small solar sails to deorbit LEO satellites without the use of an expensive propulsion system.

Simulation and Hardware-in-Loop experiments proved the feasibility of the proposed attitude control system. A magnetic-only control approach using a Y-Thompson spin is used to detumble the 3U Cubesat with stowed sail and subsequently to stabilise the sail during the deployment phase. Minituarised torquer rods and magnetic sensor hardware developed for this phase will be presented. The next phase will be to despin the deployed sail and to 3-axis stabilise the sail normal to the orbital plane, using a 2-axis translation stage for attachment of the sail to the Cubesat bus. An improved new controller including a nano Y-momentum wheel will be discussed and the performance results presented. To accurately determine the solar sail’s attitude during the sunlit part of the orbit, an accurate wide field of view dual sensor to measure the sun vector and nadir vector was developed. The performance and calibration results for this new Cubesat sensor, named as CubeSense, will also be presented.

I. INTRODUCTION

Recently the first solar sails have been launched and successfully deployed in space, i.e. 1) the JAXA Ikaros mission\(^1\) deployed a 200 square meter sail in June 2010 on its way towards Venus and 2) NASA’s Nanosail-D2 Cubesat\(^2\) deployed a 10 square meter sail in January 2011, while orbiting at 650 km in a low earth orbit. Ikaros is stabilised as a 2 rpm spinning sail with embedded blocks of LCD panels to control the spin attitude by adjusting the LCD reflectance. Nanosail-D2 is only passively stabilised by the atmospheric drag force on the sail and therefore not used to demonstrate solar sailing.

The Cubesail mission will be the first to demonstrate a practical attitude control system\(^3\) to 3-axis stabilise a solar sail and demonstrate solar sailing in low earth orbit. The 25 square meter solar sail will deploy from a 3U Cubesat of approximately 3 kg. To avoid the cost and technical challenges of developing a large solar sailing spacecraft, it is possible to demonstrate the benefit of low-mass-to-sail-area missions on a Cubesat platform in LEO as successfully demonstrated by Nanosail-D2. The aim will be to actively control the solar sail within the orbit plane at an altitude above 750 km to minimise aerodynamic drag and maximise the solar pressure force on the orbital dynamics. Simulation studies of a typical 800 km, initially 09h30 LTDN (local time descending node) sun-synchronous circular orbit, predict an approximate 2 degree inclination decrease in 260 days\(^4\). Thereafter the RAAN precession of the orbit will have reduced the sun incidence angle (to the orbit normal) to a level where the satellite will be constantly exposed to the sun and further inclination changes will cease. Figure 1 shows the typical orbit geometry in LEO of the solar sailing Cubesat. Figure 2 shows the solar sail Cubesat in stowed and deployed configuration.
II. ATTITUDE CONTROL MODES

The various attitude control modes are summarised in this section. The first control mode (Mode 1) will be used to detumble the satellite initially, when the sail is still stowed and the solar panels already deployed. This mode can also be used for safe mode stabilisation during and after sail deployment. The only sensor measurements required during Mode 1 will be the magnetometer B-field vector and the MEMS rate sensor for the body YB spin.

Control Mode 1: To safely deploy the solar sail it is necessary to first detumble the satellite. A Bdot magnetic controller is used to dump the body XB and ZB axes angular rates and align the YB axis normal to the orbit plane. A Y-Thompson Spin controller is also used to control the YB spin rate to -12.5 °/s (inertially referenced). This rate is required to have a sufficiently large centrifugal force to assist in the sail deployment, but small enough to decrease the stress experienced by the solar sail film during its deployment. The Bdot and Y-Thompson controllers as implemented, are:

\[
\begin{align*}
\dot{\beta} &= \arccos\left(\frac{B_y}{|B|}\right) \\
M_y &= K_d \frac{d\beta}{dt} \quad \text{for} \quad \beta = \arccos\left(\frac{B_y}{|B|}\right) \\
M_x &= K_s (\omega_x - \omega_{x-ref}) \text{sgn}(B_x) \quad \text{for} \quad |B_x| > |B_y| \\
M_z &= -K_s (\omega_z - \omega_{z-ref}) \text{sgn}(B_z) \quad \text{for} \quad |B_z| > |B_x|
\end{align*}
\]

Where, \(M_{PWM} = [M_x \ M_y \ M_z]^T\) a pulse width modulated magnetic moment vector of the torquer rods, \(B_{meas} = [B_x \ B_y \ B_z]^T\) is the magnetometer measured B-field vector, \(K_d\) and \(K_s\) are the detumbling and spin controller gains, \(\beta\) is the angle between the body YB axis and the local magnetic field vector, \(\omega_{x-ref}\) is the YB body spin rate reference and \(\omega_{z}\) is the MEMS rate sensor measurement.

During the deployment of the solar sail, the spinning rate is reduced to -0.25 °/s as a result of the conservation of angular momentum. The next control mode (Mode 2) will be used to nominally 3-axis stabilise all attitude angles to within 5 degrees of the reference, i.e. to keep the solar sail within the orbit plane (zero the roll and yaw angles), while tracking a pitch reference angle if required. The higher accuracy sensors, e.g. the sun and nadir sensors will be used to estimate the satellite’s attitude quaternion and angular rate vectors during Mode 2.

Control Mode 2: After initial sail deployment or safe mode detumbling, 3-axis attitude stabilisation of the satellite is achieved using a cross-product magnetic controller, while simultaneously adjusting the solar sail’s centre of pressure (CoP) relative to the satellite centre of mass (CoM). The Cross-Product controller utilises a proportional-derivative (PD) quaternion feedback error vector \(e\), as calculated in equation [2] to determine the required magnetic moment vector in equation [3].

\[
e = \begin{bmatrix}
80\dot{\omega}_x + 0.2\dot{q}_1 \\
180\dot{\omega}_y + 0.3\dot{q}_2 \\
80\dot{\omega}_z + 0.2\dot{q}_3
\end{bmatrix}
\]  \[e = \begin{bmatrix}
80\dot{\omega}_x + 0.2\dot{q}_1 \\
180\dot{\omega}_y + 0.3\dot{q}_2 \\
80\dot{\omega}_z + 0.2\dot{q}_3
\end{bmatrix}
\]

\[
M_{PWM} = e \times B_{meas} / |B_{meas}|
\]

Where, \(\hat{\omega}_{B/I} = \begin{bmatrix} \hat{\omega}_{x} \hat{\omega}_{y} \hat{\omega}_{z} \end{bmatrix}^T\) is a Kalman rate filter estimation of the body rate vector (orbit referenced) and \(\hat{q} = [\hat{q}_1 \ \hat{q}_2 \ \hat{q}_3]^T\) the vector part of the Triad estimated attitude quaternion. The Kalman rate filter uses successive measurements of the sun sensor to accurately estimate the inertially referenced body rate vector \(\hat{\omega}_{B/I}\). The sun and nadir vector measurements in body coordinates, with modelled sun and nadir reference vectors in orbit coordinates, is then used to calculate the satellite’s attitude rotation matrix \(A[\hat{q}]\) (referenced to the orbital frame) using a Triad algorithm. The estimated attitude rotation matrix can then be used to obtain the angular body rate vector (orbit referenced) from the Kalman estimated rate vector (inertially referenced),

\[
\hat{\omega}_{B/I} = \hat{\omega}_{B/I} + A[\hat{q}]_0 \ \omega_0 \ 0^T
\]

With \(\omega_0\) the satellite’s orbital rate. The solar sail is attached to a 2-axis translation stage, allowing for the
adjustment of the solar sail along two body axes. The solar sail CoP to CoM relative position is adjusted to obtain control torques around the $X_B$ (roll) and $Z_B$ (yaw) axes, respectively. The Translation quaternion feedback PD control law used, is:

$$
\begin{bmatrix}
\dot{r}_{con-x} \\
\dot{r}_{con-z}
\end{bmatrix} =
\begin{bmatrix}
120\delta_{oz} + 0.6\dot{q}_3 \\
-120\delta_{ox} - 0.6\dot{q}_1
\end{bmatrix}
$$

Where, $r_{con-x}$ and $r_{con-z}$ represents the solar sail controller’s adjusted centre position on the $X_B$ and $Z_B$ axes. Both the Cross-Product [2] and Translation [5] controllers use the estimated angular rates and attitude quaternion. These estimates depend on the sun and nadir vector measurements, only obtainable during the sunlit part of each orbit. Therefore, during the eclipse part of each orbit no active control can be done. The final control mode (Mode 3) utilises a nano momentum wheel aligned to the $Y_B$ body axis to prevent the solar sail to drift away from the zero roll and yaw attitude. The attitude drift will happen as a result of external disturbance torques on the uncontrolled solar sail panel.

**Control Mode 3:** In this mode the Y-momentum wheel will ensure gyroscopic stiffness to the roll and yaw axes through the $Y_B$ direction angular momentum vector. The pitch rotation around the $Y_B$ axis can be controlled by implementing a quaternion feedback $Y$-wheel PD controller to compute the $Y$-wheel torque requirement:

$$N_{yw/h} = K_{dy}\dot{\omega}_{oy} + K_{dy}\dot{q}_{2e}$$

Where, $K_{dy}$ and $K_{dy}$ are the proportional and derivative controller gains for optimal damping and $\dot{q}_{2e}$ is the quaternion error for a desired pitch reference attitude. To prevent momentum build-up on the $Y$-wheel, the Cross-Product magnetic controller of equation [2] must be modified to also regulate the $Y$-wheel angular momentum to a constant reference value $h_{nyy-ref} = -0.015$ Nms (50% of the maximum wheel momentum capacity):

$$e = \begin{bmatrix}
80\delta_{ox} + 0.2\dot{q}_1 \\
200(h_{nyy} - h_{nyy-ref}) \\
80\delta_{oz} + 0.2\dot{q}_3
\end{bmatrix}$$

### III. ADCS HARDWARE

This section presents the attitude actuators and sensors to actively control the solar sail’s attitude. A summary of the important features of the ADCS sensors and actuators used, is listed in Table 1.

<table>
<thead>
<tr>
<th>Sensors &amp; Actuators</th>
<th>Type</th>
<th>Range / FOV</th>
<th>Accuracy (RMS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnetometer</td>
<td>3-axis MagR</td>
<td>± 60 μT</td>
<td>&lt; 40 nT</td>
</tr>
<tr>
<td>Sun Sensor</td>
<td>2-axis CMOS</td>
<td>Hemisphere</td>
<td>&lt; 2º peak</td>
</tr>
<tr>
<td>Nadir Sensor</td>
<td>2-axis CMOS</td>
<td>± 45º</td>
<td>&lt; 2º peak</td>
</tr>
<tr>
<td>Coarse Sun</td>
<td>6 Photodiodes</td>
<td>Full Sphere</td>
<td>&lt; 10º</td>
</tr>
<tr>
<td>Rate sensor</td>
<td>3-axis MEMS</td>
<td>± 20 %/sec</td>
<td>&lt; 0.01 %/sec</td>
</tr>
<tr>
<td>Sail Translate</td>
<td>2-axis Stepper</td>
<td>± 36 mm</td>
<td>&lt; 0.01 mm</td>
</tr>
<tr>
<td>Stage Motors</td>
<td>Momentum</td>
<td>BDC Motor</td>
<td>± 0.03 Nms</td>
</tr>
<tr>
<td>Pitch wheel</td>
<td>Magnetorquer Rod</td>
<td>± 0.2 Am²</td>
<td>&lt; 0.0002 Am²</td>
</tr>
</tbody>
</table>

All attitude sensors and control actuators are accessed by the Cubesat’s ADCS OBC (the onboard processor executing the ADCS code) via an ADCS Interface Module (AIM). A block diagram of this module is shown in Figure 3 below. The AIM hardware is implemented on a single PC104 board with standard Cubesat connector. The heart of the AIM consists of a low power micro-controller with several I/O ports, Analog to Digital inputs and a dual FC communication bus. The first FC bus is connected to the Cubesat’s main OBC and the second to a CubeSense module. The latter is a dual camera system with wide FOV lenses (180º FOV fisheye) to measure the sun and nadir vectors accurately. CubeSense will be discussed in more detail below. The various components of the AIM will be discussed next:

![Fig.3: ADCS Interface Module](image)

**Coarse sun sensor:** 6 Planar photodiodes will be mounted on the 6 facets of the Cubesat structure. The short circuit current from these diodes will be roughly proportional to the cosine of the sun vector angle to the
photodiode surface’s normal. A current to voltage amplifier is used for each photodiode to obtain a signal large enough for analogue to digital (A/D) conversion. The sun vector direction can then be extracted from the largest three photodiode measurements – assuming no shadowing from the deployed solar sail. The earth albedo will contaminate the measurements and reduce the sun vector direction accuracy to a RMS value of roughly 10º.

**Magnetometer:** A magneto-resistive 3-axis magnetic field sensor (HMC1053) will be mounted on a 15 cm deployable arm. The deployment will take place with the spring loaded solar panels, when the 3U Cubesat is ejected from the PPOD. The magnetometer sensor deployment away from the Cubesat body will reduce any magnetic contamination, caused by the onboard sub-systems. The three analogue output channels of the magnetometer are low pass filtered and A/D converted on the AIM.

**Momentum Wheel:** A brushless DC motor (BDCM) driver on the AIM will be used to accurately control the speed of a nano inertia disc mounted to a BDCM. The disc will rotate at a nominal reference speed of 4000 rpm (50% of maximum) resulting in an angular momentum vector (magnitude of 0.015 Nms) along the body YB axis. Figure 4 shows the 25.5 gram momentum wheel unit.

**Magnetorquer Rods:** Three magnetorquers (MT) are used to generate a controlled magnetic moment in all body axes. By pulse width modulation (PWM) of the MT currents a magnetic moment vector in a desired direction and size can be obtained. Figure 5 shows the 22 gram MT of length 60 mm and 10 mm diameter. The torquers are manufactured using a low remanence ferromagnetic core (Supra-50) with thin copper windings. A maximum magnetic moment of 0.2 Am² is obtained using 2.5 V at 83 mA current (200 mW). These maximum values are obtained at a 50% PWM duty cycle.

**Translation Stage:** A 2-axis translation stage connects the solar sail panel to the main Cubesat body. Two micro stepper motors with gear boxes (8 mm diameter and mass less than 8 gram (see Figure 6) are used to move the solar sail ± 36 mm along the Xs and Zs body axes. The size and mass of the stepper motors were important factors in the translation stage design as they contribute to the overall mass and height of the design. See Figure 7 for a prototype of the mechanical translation stage. The dimensions are constrained by the Cubesat dimensions, the prototype structure being 100 x 100 x 25 mm with a mass of only 81.5 gram.

**CubeSense:** A new dual camera sensor was developed for the solar sail Cubesat. The sensor is based on a low power CMOS camera module of 640 by 480 pixels with a 190° FOV fisheye lens. The one camera is used as a sun sensor with an added 0.01% neutral density filter to reduce the sun illumination levels on the camera pixels. This camera will measure the sun vector direction in a full hemisphere. The other camera will be used to measure the nadir vector by doing some signal processing on the illuminated earth disc measurement in its hemispherical FOV.
The CubeSense module is using an FPGA to read an image at the fast clock-out rate of the camera into a SRAM. A low power microcontroller (MCU) is then used for the required image processing to determine the sun and nadir vectors. Figure 8 is a block diagram of the module hardware as implemented on a Cubesat standard PC104 board with bus connector for power and an I²C comms interface. Figure 9 shows a picture of a typical CubeSense unit. The dual (sun and nadir) cameras can be mounted with boresights in opposite directions (as in Fig.9), but can also be mounted with boresights in orthogonal directions. The latter configuration will be used in the solar sail mission, with the sun sensor in the body $Y_B$ direction and the nadir sensor in the body $Z_B$ direction.

- Edge detection – To determine where the earth and the sun is
- Distortion correction – To correct the effect of the fisheye lens on the image
- Centroid calculation – To calculate the body frame coordinates of the sun and nadir centroid in the image

Figure 10 shows a typical sun image and the zoomed-in image with all the pixels above the threshold to be used in the centroid calculation.

The distortion model for the fisheye lens with significant barrel distortion, can be implemented as a third order polynomial (see Figure 11). To reduce processing in the CubeSense MCU, a lookup table with linear interpolation is used.

Calibration testing of CubeSense showed a maximum angle error in the nadir vector of less than 0.5° with the full earth disc in view (boresight within ± 35° from nadir). As the visible portion of the earth disc moves outside the image FOV the maximum angle error increased to 5° at ± 50° from nadir. Figure 12 shows the typical measurement accuracy from the nadir camera.
The sun sensor having a smaller image and well defined centroid shows a better accuracy over the full hemispherical FOV. As expected, the sun vector angular accuracy will be best at the camera boresight and decrease towards the edge of the FOV, when the sun image decreases as a result of the lens distortion. From Figure 13, it can be seen that the sun angle accuracy varies from 0.1º at boresight to about 2º at the edge of the FOV.

CubeSense is also ideal for a Cubesat application, due to the following features:

- Low power – On active standby the module only use 62 mW of power, the maximum power is 432 mW when both images are taken and loaded into the SRAM – this is only required for 48 milliseconds
- Low mass – The total mass with dual cameras and fisheye lenses is only 110 gram

IV. ADCS SIMULATION RESULTS

The orbit used for the simulation tests is an 800 km circular sun-synchronous orbit. The orbit elements used are presented in Table 2. The simulation was executed using a sample period of one second for all models, controllers and estimators. In practice the sampling period of the onboard control loop can be increased to at least ten seconds, without any noticeable degradation in performance (due to the slow open and closed loop dynamics). However, for the simulation accuracy of the numeric integrators it was decided to implement the simulation loop at 1 Hz.

A SGP4 model was used to simulate the satellite’s orbit in combination with an accurate sun orbit model. The geomagnetic field was simulated using a 10th order IGRF spherical harmonic model. The aerodynamic drag and solar radiation disturbance forces were modelled, taking into account the properties and attitude of the 25 m² solar sail, relative to the atmospheric velocity and the sun vector directions respectively. These models are presented in more detail in the reference paper³.

<table>
<thead>
<tr>
<th>Orbit Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Semi-major axis</td>
<td>7173.7 km</td>
</tr>
<tr>
<td>Initial Inclination</td>
<td>98.39º</td>
</tr>
<tr>
<td>Orbital Period</td>
<td>6046.8 sec</td>
</tr>
<tr>
<td>Eccentricity</td>
<td>0.0009</td>
</tr>
<tr>
<td>Sun-synchronicity</td>
<td>LTDN 09h30</td>
</tr>
</tbody>
</table>

Table 2: Orbit used for the Solar Sail ADCS Testing

All the ADCS sensors were modelled with realistic measurement noise and slow varying offset errors where applicable (reference paper³). The ADCS actuators were modelled with their saturation and quantisation limits.

The remainder of this section will present the simulation results graphically from typical initial conditions for the various control modes (Section II).

Control Mode 1: Detumbling after sail deployment using the Bdot controller [1] and MEMS rate sensor for direct measurement of the body $Y_B$ angular rate. The initial roll, pitch and yaw angles are -45º, 0º and 45º respectively. The initial angular rate vector (orbit referenced) is: $\omega_{B/o} = \begin{bmatrix} 0.3 & -3 & -0.3 \end{bmatrix}^T$ °/sec. Figure 14 shows how the $X_B$ and $Z_B$ orbit referenced body rates are damped within 0.5 orbits (the shadowed bands are the eclipse periods). The $Y_B$ body rate took about 3 orbits to decrease from from -3 °/sec to -0.25 °/sec.
**Control Mode 2:** After detumbling a transition to full 3-axis stabilisation, keeping the solar sail within the orbit plane, is affected using the Cross-Product [2,3] and sail panel Translation [5] controllers. The angular rate vector is estimated by a Kalman rate filter using the sun vector measurements. The attitude is estimated by a Triad algorithm from sun and nadir vector measurements. The initial roll, pitch, yaw angles are -5º, 20º and 5º respectively. The initial angular rate vector (orbit referenced) is: \( \omega_{B/O} = [0.0 \ -0.25 \ 0.0]^T \) °/sec. Figure 15 shows how the pitch angle takes about 2.5 orbits to stabilise. The roll and yaw angles are stabilised within one orbit. It is also important to remember that the controllers are active only in the sunlit part of each orbit, when rate and attitude estimates can be made.

Figure 16 shows a typical Control Mode 2 performance from small initial attitude errors – i.e. from the same conditions as used above, but zero initial angular rates. The average RMS attitude error is 2.3° over the last three orbits, once all attitude angles have been stabilised. Figure 17 shows the corresponding sail panel translation controller output staying well within the ±36 mm range limit and not controlling within the eclipse part of the orbit.

**Control Mode 3:** The addition of a Y-momentum wheel with Y-wheel pitch controller [6] and an adaption of the Cross-Product [7] controller, improved the performance results of Control Mode 2. The gyroscopic stiffness of the momentum wheel to the roll and yaw axes helped to reduce the yaw drift during eclipse, as evident in Figure 16. The initial conditions are similar to those in
the simulation tests for Control Mode 2. Figures 18 and 19 can therefore be compared respectively to Figures 15 and 16 to see the performance improvement.

Fig.18: Control Mode 3 Performance from Detumbling

Fig.19: Control Mode 3 Stabilisation Performance

The average RMS attitude error is now reduced to 1.6º, again measured over the last three orbits, when all attitude angles have been stabilised and the Y-wheel momentum reference has been reached. Figure 20 shows how the Y-wheel angular momentum has increased from 0 to -0.015 Nms by utilising the magnetic Cross-Product [7] controller. The initial disturbance in the pitch angle during the first orbit in Figure 19 is mainly caused by the magnetic controller, during the increase of the Y-wheel angular momentum.

V. CONCLUSIONS

The paper presented a feasible and practical attitude determination and 3-axis control system of a small solar sail to be deployed from a 3U Cubesat. Many new attitude control sensors and actuators were specifically designed for this mission. Their mass, power, volume and performance characteristics satisfy the Cubesail mission requirements, while presenting many new features opening new frontiers for future Cubesat missions.

Fig.20: Y-Wheel Angular Momentum Management

The paper is complementing a previous paper [6], by presenting more detail on the developed ADCS sensors and actuators. The novel CubeSense dual wide-FOV sun and nadir sensor’s design, expected performance and calibration results are also presented in Section III. The three control modes are explained in Section II and the improved performance results of Control Mode 3 with an added Y-momentum wheel are evident from the simulation results in Section IV.

To reduce mission risk, all three control modes will be able to keep the solar sail deployed within the orbit plane to ensure mission success (i.e. to demonstrate an inclination change in an initial sun-synchronous orbit as a result of solar radiation pressure). The main risk being non-ideal deployment of the 5 x 5 meter solar sail. The ADCS was therefore designed from a redundancy point of view and to demonstrate an increase in performance, for the successively more advanced control modes (from a Y-spinning to fully 3-axis stabilised solar sail).

All the controllers (except for the sail Translation controller) and estimators have been flown successfully in orbit on other small satellites [4-7, 8], but this implementation will be a first for a Cubesat mission. The ADCS code has already been Hardware-in-Loop tested on a new low
power Cubesat OBC with floating point capability (paper still to be published) and all the critical timing requirements have been met.

The results from this mission will also satisfy all the ADCS goals of a future DeorbitSail mission, i.e. an EU FP7 project to demonstrate rapid deorbiting at end-of-life of satellites by deployment of small solar sails.

VI. ACKNOWLEDGEMENTS

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