Lesson Learned in the Operation of a CubeSat ADCS in the Presence of Sensor Anomaly

Angel B. Menendez Cifuentes*
Aeronautics and Astronautics Engineering
National Cheng Kung University
Tainan City, Taiwan
P48087081@gs.ncku.etu.tw

Frederic Wilhelm Bremecker
Aerospace and Automotive Engineering
FH Aachen
Aachen, Germany
frederic.bremecker@alumni.fh-aachen.de

Jyh-Ching Juang
Electrical Engineering
National Cheng Kung University
Tainan City, Taiwan
8202019@gs.ncku.edu.tw

***Abstract*—Small satellites and CubeSats often employ commercial off-the-shelf (COTS) components to achieve cost effectiveness, but these components are prone to anomalies that may jeopardize mission success. It is thus desired to learn from operational experience for continuous improvement. In the paper, lessons learned from the operation of the Lilium-1 CubeSat attitude determination and control subsystem (ADCS) are discussed. Lilium-1 is a 3U CubeSat designed and operated by the NCKU team that was launched in 2023. It has essentially accomplished its missions on S-band communication, space IoT, and Earth observation. The ADCS consists of three-axis gyroscope, three-axis magnetometer, fine Sun sensor, and Earth infrared sensor for attitude estimation. In late 2025, the magnetometer experienced complete signal loss, leading to the loss of attitude control. Following this failure, even the use of a Kalman filter with the remaining sensors proved insufficient for reliable operation. To address this anomaly, a ground-based recovery strategy is proposed. An SGP4 orbit propagator combined with IGRF data is used on a ground computer to calculate local magnetic field vectors at a target orbital location T and n preceding points, where T and n stand for the look-ahead (or predicted) locations and time epochs. These vectors are converted into hard-coded magnetorquer command sequences such that the equilibrium zero-torque attitude aligns the magnetorquers with Earth's magnetic field at each step. The commands, each associated with a specific execution time, are uploaded to the onboard computer (OBC) to perform an increasingly accurate step-wise attitude alignment, culminating at T. The proposed methodology and its limitations are characterized through testing with a different number of n points and time spacing; attitude is confirmed through images taken at T. The results indicate that by-passing onboard attitude estimation by ground-based prediction appears to be able to recover the satellite from catastrophic magnetometer loss.**

***Index Terms*—Attitude Determination Control Subsystem, Fault Recovery, CubeSat, Magnetometer.**

I. Introduction

CubeSats have proven their worth as commercial and scientific assets which is reflected in the exponential growth of their launches since the standard was published in the early 2000s [1]. They have enabled many countries to access space for the first time because the widespread availability of standardized components and service providers make their costs relatively low and development time short. These strengths also make them attractive to companies that want to mass produce constellations, as long as they can overcome the intrinsic scalability challenges like attitude-determination sensors calibration in orbit [2]. Some universities that focus on scientific payloads or technology demonstration can also maintain their CubeSat development agility by reutilizing a basic bus and then adapting their mission analysis for each specific case [3].

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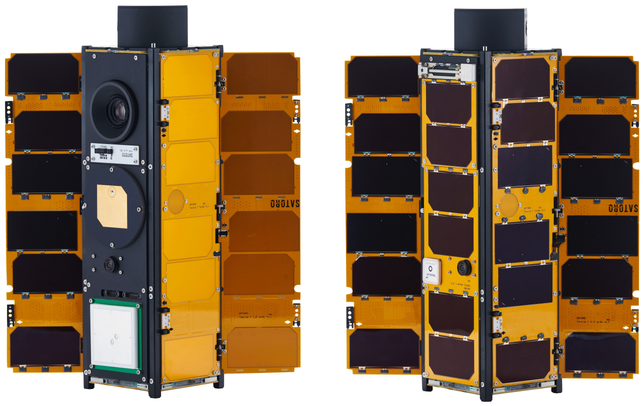
Spacelab at National Cheng Kung University (NCKU-Spacelab) has developed more than ten CubeSats since its foundation in 2002, with the most recent launches being Lilium-1 (3U) in 2023 [4], and Lilium-2 along with Lilium-3 (6UXL) in November 2025 [5], [6]. According to Langer and his spacecraft reliability study, CubeSats tend to fail mostly in their initial stages in a right-open bathtub-curve [7]. However most of these failures can be addressed and prevented during the early project stages with the appropriate project management and *test-like-you-fly* paradigms. NCKU-Spacelab was not immune to pre-launch mistakes and one of the early satellites, IRIS-A [8], was inadvertently missconfigured with its magnetorquer polarities inverted. This caused increasing rotation rates on all axis during the commissioning phase but fortunately the root cause was correctly identified by the ground team, control was regained, and the mission was concluded successfully [9].

At the other end of the curve, all components are prone to failure due to tear and wear, and the limited size and budget associated to CubeSats don't always allow for system redundancies. This paper will focus on the strategies utilized to recover the attitude control of Lilium-1 after it experienced a complete magnetometer loss during its extended mission phase. At this point it had already fulfilled its technology demonstration mission, but in the context of university-built CubeSats, extending the mission beyond a component's statistical breaking point provided valuable learning opportunities that we now wish to share.

II. Lilium-1 CubeSat

Lilium-1 is a 3U CubeSat launched into Sun-Synchronous Orbit (SSO) by a SpaceX Falcon 9 rocket on December 2, 2023. Figure 1 shows Lilium-1 after the Assembly, Integration,



(a) (b)

Fig. 1. (a) Lilium-1 (+Z view). (b) Lilium-1 (-Z view).

and Testing (AIT) milestone. Its main payloads are a 1U dedicated Artificial Intelligence Remote Sensing (AIRS) camera, which works together with an S-band downlink directional patch antenna for a space-based Point, Acquire, Transmit (PAT) procedure demonstration. It also has an IoT antenna with a digipeater used for educational purposes and outreach programs, and some minor experiments that include an in-house built solar panel deployable system and a small *SelfieCam* mounted on the tuna can.

The main payloads are highly sensitive to pointing direction, so the requirements for the ADCS were having a pointing knowledge of $\pm 1°$ and point accuracy of $\pm 3°$. The system worked consistently enough that the student-led team was able to take pictures for damage assessment of wildfires within 48 hours of their occurrence. Figure 2 shows one of such pictures taken in late 2024, where the upper right half of the picture shows burned fields near Chico, California. This is the baseline of what *Nominal Operations* means for a CubeSat like Lilium-1 at NCKU-Spacelab.

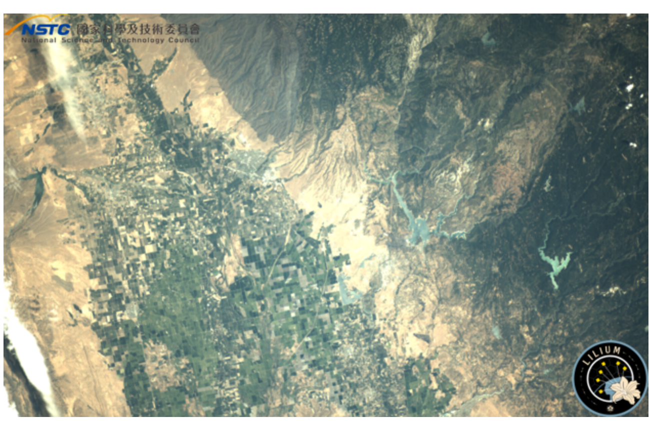


Fig. 2. Chico, California (39.8, -121.8) 2024/08/20.

III. Attitude Control Recovery Strategy

The ground team attempted to recover the magnetometer signal for several weeks but eventually it became obvious that the component was completely lost. A mission-oriented recovery approach was taken: even if control could not be attained at all times, as long as the spacecraft could be correctly oriented when executing a mission, this is considered a success. Going forward, the decision is made to move computations to the ground and completely bypass the attitude determination in the ADCS. The satellite TLE is obtained from the NORAD database, then an SGP4 orbit propagator combined with IGRF data is used on a ground computer to calculate local magnetic field vectors at a target orbital location T and n preceding points, where T and n stand for the look-ahead (or predicted) locations and time epochs. Then these vectors are converted to hard commands in a script that is uploaded to Lilium-1 and then executed by the magnetorquers at the appropriate time. To maximize the magnetorquer output, the expected geomagnetic field vector $\mathbf{V}$ is normalized by its largest absolute component, i.e.,

$$\mathbf{V}_{\text{norm}} = \frac{\mathbf{V}}{\max_i |V_i|}, \tag{1}$$

ensuring that $|V_{\text{norm}}(i_{\max})| = 1$ while preserving the relative scaling of the remaining components.

One limitation that needs to be addressed is that due to the nature of this agnostic control method, only magnetorquer commands could be computed *a priori* from the ground which are independent of the instantaneous state of the spacecraft during its execution. The torque generated by the magnetorquers τ_{Dipole} is dependent on Earth's magnetic field B at the instantaneous location of the spacecraft in orbit, by the relationship $\tau_{\text{Dipole}} = m \times B$. This means its not possible to generate a torque if Earth's magnetic field is already aligned with the magnetorquer m at a given location. Ergo, it is considered an underactuated ADCS control scheme as described by McKeen [10].

Several schemes of selecting the preceding points to targets were tested to compare their performance. For consistency between the first two schemes, an equal amount of control points $n = 5$ is selected, with $n_5 = T$ being the last control point. The first scheme has equal intervals of thirty seconds between n points, making $t(n) = [-120, -90, -60, -30, 0]$s. The second scheme makes the intervals converge as it approaches the target, so that $t(n) = [-300, -180, -90, -30, 0]$s. The third scheme was more elaborate. First, the magnetic field vectors were calculated every second in the expected trajectory of the spacecraft prior to target T. Second, a maximum magnetic field difference $\Delta\text{mag} = 1500\text{nT}$ was selected between these instantaneous magnetic field vectors within a period of four minutes before reaching T . Third, the n points prior to the target T were selected based on this Δmag rather than specific times.

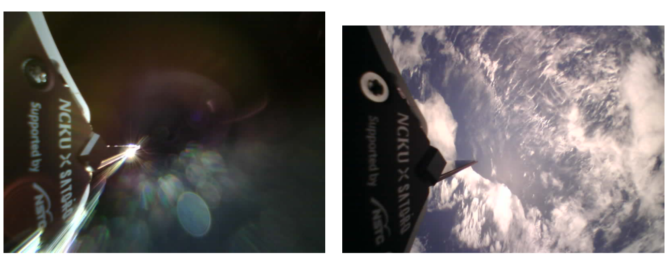
Since the system's ability to determine its attitude was significantly impaired, a picture was taken at the target location T and paired with the data recorded. Success would then be considered by whether a plateau in rotation rates was observed in the data and if the picture was taken at the desired target. A similar approach is used by [2] to calibrate their constellation's

ADCS at scale, where they command pictures to be taken at geo-referenced locations and then the appropriate adjustments are made. We do not have such a large scale database of georeferenced imagery, but the pictures can be analyzed by the ground team directly and estimate whether the maneuver succeeded or not. Additionally, one more limitation is that the ADCS system is COTS and we don't have full knowledge of the estimation algorithm. So, the data acquired is expecteed to have high accuracy between tests, but its overall precision cannot be fully quantified.

From the satellite operations point of view, the S-band downlink effectiveness is directly linked to the attitude control of the satellite, which would compound the complexity of the experimental design because both schemes at target T and at the downlink location would have to succeed accordingly. Therefore, it was decided to take a low-resolution image with the *SelfieCam* that can be easily downloaded via the omnidirectional UHF antennas in Lilium-1. This also represents an operational choke-point; each test takes about one week to compute/upload the magnetorquer commands, execute at desired location, and download the image along its corresponding ADCS data.

IV. Results and Discussion

As a baseline of operations under magnetometer loss, during the fault detection and attempt of signal recovery process, 16 images were taken and 14 of them look similar to Fig. 3a, where nothing can be observed other than the Lilium-1 frame and the emptiness of space. One exception was Fig. 3b, which was pointing towards Earth, but this result is consistent with what is expected from taking pictures at a randomized pointing state.



(a) (b)

Fig. 3. (a) Image above Taiwan with no control 2025-09-16. (b) Image above West Philippine Sea with no control 2025-12-08.

Eleven tests were made as summarized in Table I. Here, tests 1, 2, 5, 9, and 10 failed because the team was unable to upload the complete set of magnetorquer commands to the spacecraft before the projected time of execution. This shows several limitations, starting with the SGP4 propagator, because it is only accurate within a certain time frame after computation. Then, an upper limit of 72 hours was decided from the time of ground computation to the mission execution and this was not always enough to upload everything. Also, sometimes communication with the spacecraft seemed more difficult than under nominal operation conditions.

TABLE I
Results Summary

Test	Scheme	Location	Data Result	Image Result
1	Equal int.	Taiwan	Script upload failure	
2	Equal int.	Mt. Fuji, Jap.	Script upload failure	
3	Equal int.	Aachen, Ger.	Successful	Successful
4	Equal int.	Guatemala, Gt.	Successful	Successful
5	Converging	Mt. Fuji, Jap.	Script upload failure	
6	Converging	Aachen, Ger.	Successful	Successful
7	Converging	Guatemala, Gt.	Successful	Unsuccessful
8	Mag. delta	Paris, Fr.	Successful	Unsuccessful
9	Mag. delta	Warsaw, Pol.	Script upload failure	
10	Mag. delta	Madrid, Sp.	Script upload failure	
11	Mag. delta	Madrid, Sp.	Successful	Successful

On the bright side, when the full set of commands was successfully uploaded to Lilium-1, control during mission operation improved significantly over random-pointing operations. Both tests over Germany and Guatemala succeeded in observed plateaus and image taking using the equal interval preceding control points. Then plateaus in the rotation rates were observed using the other methods but they didn't always succeeded in staying at the desired attitude to correctly take the picture at target T.

Figure 4 shows the two successful results of the first scheme, where all the control points were equally spaced every thirty seconds. The left column (figs. 4a and 4f) show in yellow the control points n in the map where magnetorquer outputs were executed and the target point T is marked in red. Then the middle column (figs. 4b and 4g) shows the attitude of Lilium-1 at the moment that the picture was taken, here the red dots in the center mark the position of the main AIRS camera (for reference) and the red dots at the edge represents the position of the *SelfieCam* that was used to take the picture. Earth is represented in blue at the bottom of these figures. Then, figures 4d and 4h show the Euler angles and rotation rates. It can be seen how during the control period they decrease compared to before and after.

Similarly, figure 5 shows a set of figures for two results of the preceding converging control points scheme. Here it was hypothesized that having control points further behind would help mitigate greater initial rotation rates, but figure 5d shows that although the rotation rates did decrease, the Euler angles look very similar before, during and after the control stage. Then, in figure 5g Earth can still be seen but it is already misaligned as the correct attitude could not be maintained long enough in this test.

In the third scheme, 5-7 commands were setup to fit the goal of having a $\Delta\text{mag} \leq 1500\text{nT}$ in the period prior to T. This increased the amount of commands to be uploaded and the complexity of the operation significantly. Unfortunately the results were less than ideal for all the extra work. It seems that a simpler and more blunt approach is more effective, but further testing is recommended at greater scale to have a statistically more complete understanding. The authors recommend testing at locations where the system would be underactuated and to increase the variability in the initial states.

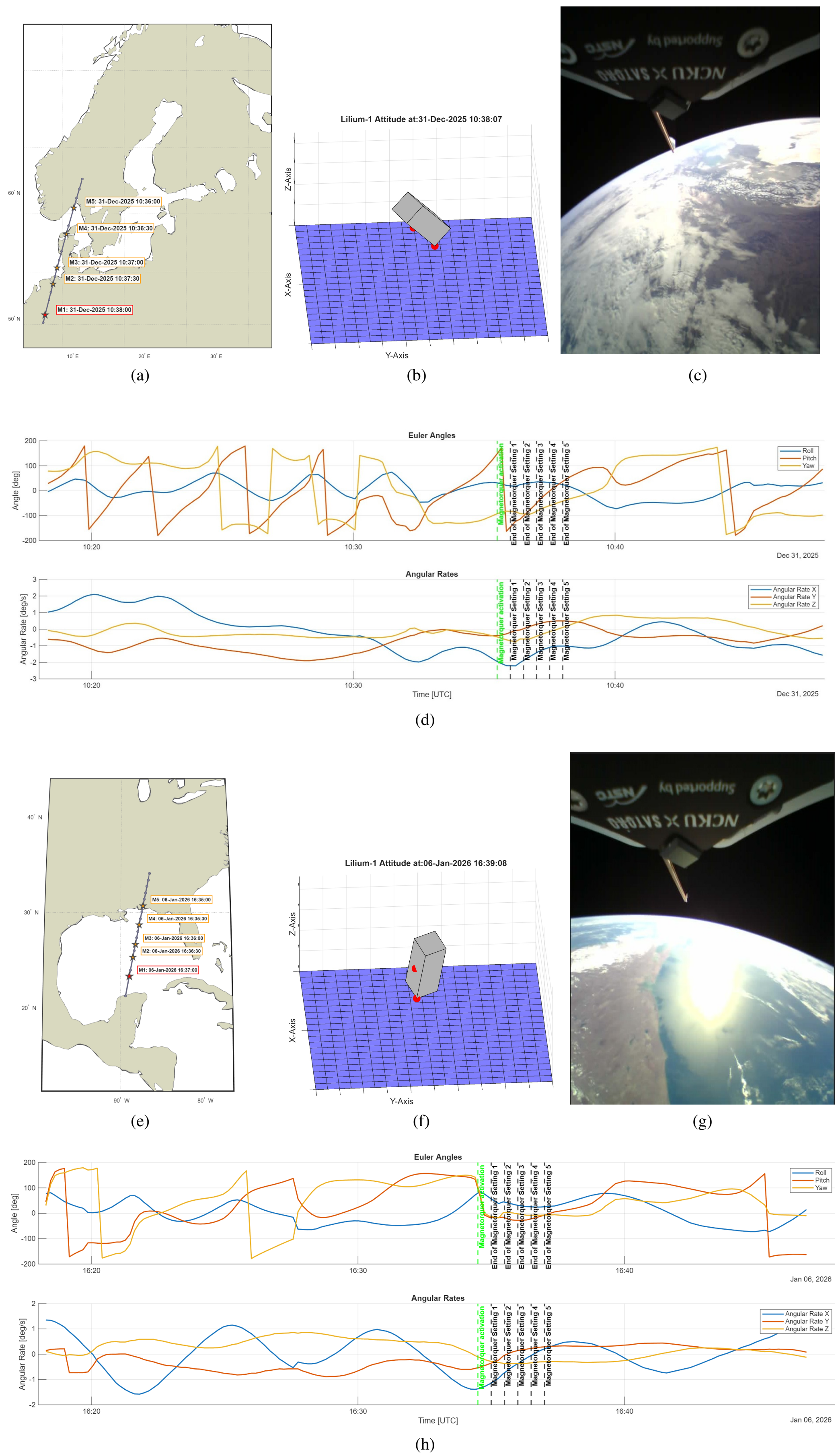


Fig. 4. Tests with preceding control points at equal intervals.

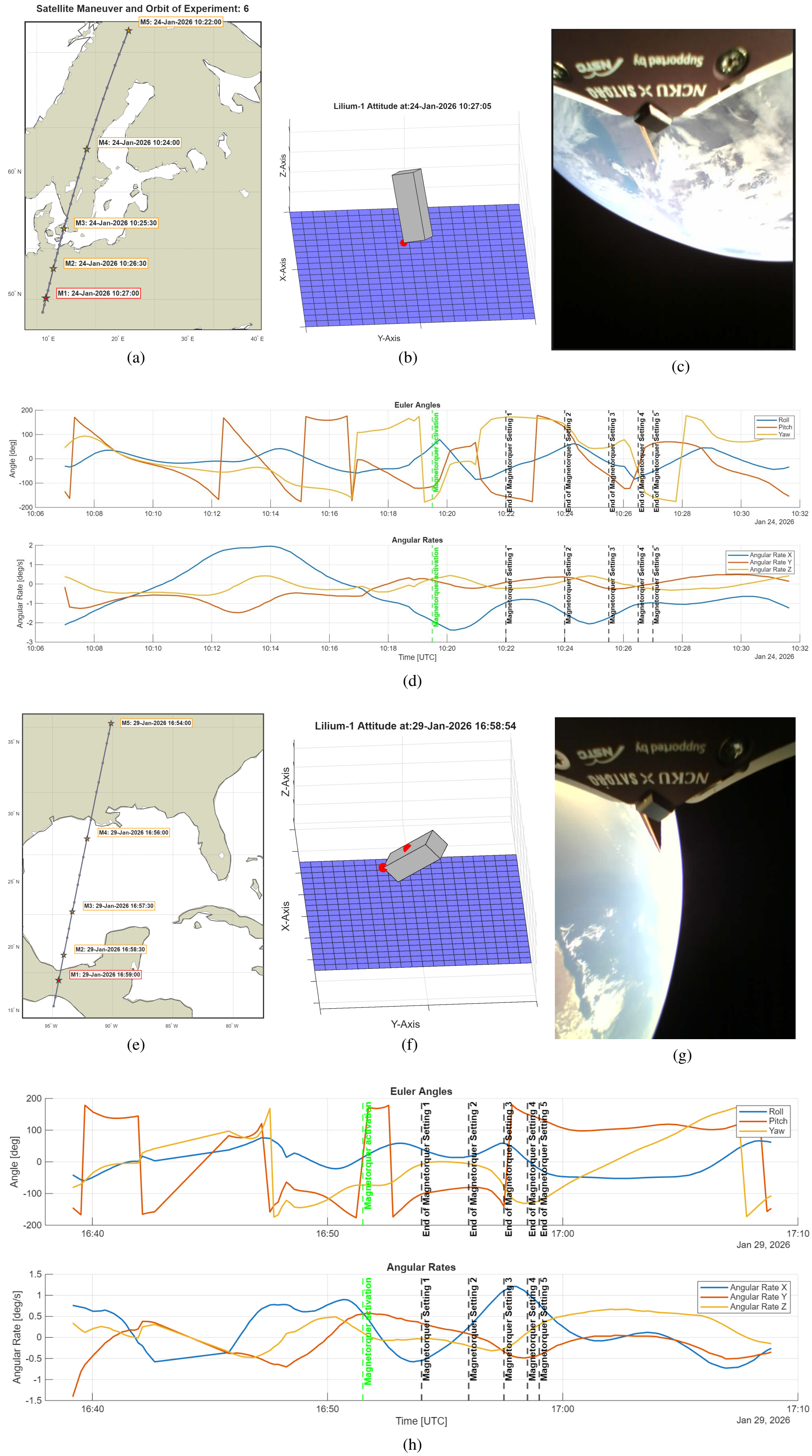


Fig. 5. Tests with preceding converging control points.

V. Conclusions

The Lilium-1 CubeSat, which was launched in 2023, has successfully accomplished its missions on S-band communication, image acquisition, and internet-of-thing experiment. Yet, as the CubeSat adopts some COTS, the reliability is at issue. The magnetometer of the Lilium-1 was found to be non-operational after 1.5 years. As a result, the Lilium-1 attitude cannot be controlled with the desired accuracy. The paper investigates a scheme to account for the sensor anomaly issue. The proposed methodology of magnetorquer control, agnostic of current spacecraft state, increases attitude control above attempting to control it with an under-defined attitude estimator.

From the three schemes of state-agnostic control, the simplest is the most efficient in terms of satellite operation complexity and results. It consists in commanding the magnetorquers at evenly distributed control points prior to the target.

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