

ATTITUDE DETERMINATION FOR CUBESATS USING MEASUREMENTS FROM NEIGHBOURING SATELLITES IN LOW EARTH ORBIT

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Abstract

Accurate attitude determination is essential for CubeSat navigation, communication, payload pointing, and autonomous formation-flying operations. This study investigated a cooperative attitude-determination approach in which measurements from neighbouring satellites in low Earth orbit (LEO) were integrated with conventional onboard sensors. A simulation-based quantitative research design was employed using a quaternion-based Extended Kalman Filter (EKF) supported by gyroscope, magnetometer, Sun-sensor, and inter-satellite line-of-sight measurements. A representative 3U CubeSat and three neighbouring satellites were modeled under multiple geometric and sensor-degradation scenarios using Monte Carlo simulations. The results indicated that the integration of one neighbouring satellite reduced overall attitude root mean square error (RMSE) from 2.05° to 1.26%, while three neighbouring satellites further reduced RMSE to 0.83°. Convergence time decreased from 342 s for the conventional configuration to 146 s for the three-neighbour configuration. The results also demonstrated that attitude-estimation performance was strongly influenced by neighbouring-satellite geometry and inter-satellite measurement noise. Under degraded conventional sensor conditions, cooperative estimation maintained substantially greater accuracy and robustness than the sensor-only architecture. The findings support the applicability of Wahba's problem as an underpinning theoretical framework for integrating inertial reference vectors and body-frame line-of-sight observations. Overall, cooperative neighbouring-satellite measurements demonstrated significant potential for improving the accuracy, observability, convergence, and fault tolerance of CubeSat attitude determination in future distributed LEO missions.

1. INTRODUCTION

CubeSats have evolved from primarily educational and technology-demonstration platforms into operational spacecraft capable of supporting Earth observation, scientific

investigation, communications, formation flying, and distributed space missions. This transition has increased the requirements placed on their attitude determination and control systems (ADCS), particularly because spacecraft pointing

accuracy directly influences payload performance, communication-link availability, imaging geometry, and inter-satellite operations. At the same time, CubeSats remain subject to stringent constraints in mass, volume, computational capacity, power consumption, and sensor cost. Consequently, the development of computationally efficient and robust attitude-estimation techniques remains an important research problem (Reizinger & Vajda, 2023).

Attitude determination refers to the estimation of a spacecraft's orientation with respect to an inertial or orbital reference frame. Conventional CubeSat systems commonly combine measurements from gyroscopes, magnetometers, Sun sensors, GNSS receivers, and, where higher accuracy is required, star trackers. Sensor fusion through Kalman-filter-based estimators has become an important approach because individual sensors are affected by measurement noise, bias, environmental disturbances, limited availability, or temporary loss of observability. Recent research has demonstrated that computationally efficient Kalman-filter architectures can improve CubeSat attitude estimation while reducing the computational burden imposed on small onboard processors (Reizinger & Vajda, 2023). Similarly, multiplicative extended Kalman filtering has been investigated for fault-tolerant attitude estimation of small satellites under degraded magnetometer and Sun-sensor measurements (Kinatas et al., 2025).

The increasing deployment of CubeSat constellations and formation-flying spacecraft provides an additional source of information that can potentially be exploited for attitude determination. In a distributed satellite system, neighbouring spacecraft can exchange orbital and sensor information through radio-frequency, optical, or other inter-satellite links. Relative navigation techniques based on GNSS, ranging, and optical measurements can provide information concerning the relative geometry of spacecraft. Recent research has demonstrated the feasibility of high-precision relative positioning using GNSS carrier-phase measurements in

satellite-formation scenarios, emphasizing the potential of inter-satellite measurements for distributed spacecraft missions (Cai et al., 2024). Low-cost GNSS-based formation-flying studies have likewise demonstrated the feasibility of estimating relative spacecraft positions using commercially available receivers, although measurement errors and receiver limitations remain important considerations (Forero et al., 2025).

The availability of neighbouring satellites introduces an opportunity to extend conventional attitude determination from a single-spacecraft sensor-fusion problem to a cooperative estimation problem. If the relative position of a neighbouring satellite is known and its line of sight can be measured in the body frame of the target CubeSat, the resulting vector observation provides an additional constraint on the spacecraft's attitude. Multiple neighbouring satellites located at geometrically diverse positions can generate multiple independent line-of-sight vectors, thereby improving the observability of the target spacecraft's orientation.

Recent research provides evidence that relative measurements can contribute to spacecraft attitude estimation. For example, a study published in 2024 developed an Unscented Kalman Filter for relative attitude estimation between two formation-flying spacecraft by combining line-of-sight measurements with gyroscope observations and spacecraft dynamics. The findings demonstrated that coupled sensor and estimator architectures can produce accurate relative attitude estimates while using quaternion-based attitude representation.

Despite these developments, most CubeSat attitude-determination research continues to focus primarily on onboard sensor fusion, while formation-flying research largely concentrates on relative position, velocity, and formation maintenance. The systematic integration of neighbouring-satellite measurements specifically for the absolute attitude determination of an individual CubeSat remains comparatively underexplored. This distinction is important because relative navigation and attitude

determination are coupled through the spacecraft body frame: an accurate inertial relative vector becomes an attitude observation when measured from the target spacecraft's body frame.

The proposed research addresses this opportunity by developing a cooperative attitude-determination framework for a CubeSat operating in low Earth orbit (LEO). The framework conceptualizes neighbouring satellites as distributed reference sources and integrates inter-satellite line-of-sight and relative-position information with conventional inertial measurements through a quaternion-based state estimator. Such an architecture could increase measurement redundancy, improve attitude observability, and provide greater resilience when conventional sensors experience temporary degradation or measurement faults.

Accordingly, the study investigates whether measurements obtained from neighbouring LEO satellites can be effectively incorporated into CubeSat attitude determination and whether cooperative measurements can improve estimation accuracy, convergence, and robustness compared with conventional sensor-only approaches. The research is particularly relevant to future CubeSat constellations, formation-flying missions, autonomous rendezvous operations, distributed sensing systems, and low-cost spacecraft architectures.

2. Problem Statement

Accurate attitude determination is a fundamental requirement for CubeSat missions because spacecraft orientation governs the pointing of communication antennas, optical payloads, solar panels, scientific instruments, and inter-satellite links. However, CubeSats operate under severe restrictions in mass, volume, power, computational resources, and financial cost. These constraints frequently necessitate the use of low-cost sensors whose measurements can be affected by bias, noise, environmental disturbances, magnetic interference, sensor outages, and limited observability. Although advanced sensors such as star trackers can provide high-accuracy attitude information, their

cost, computational requirements, optical constraints, and susceptibility to Sun/Earth exclusion conditions can limit their suitability for some small-satellite missions. Recent research continues to investigate computationally efficient and fault-tolerant estimation methods because these constraints remain significant for small spacecraft (Reizinger & Vajda, 2023; Kinatas et al., 2025).

The problem becomes more pronounced when a CubeSat operates as part of a constellation or formation. Conventional attitude determination treats neighbouring spacecraft primarily as communication or navigation partners rather than as additional sources of attitude information. Yet, neighbouring satellites inherently provide potentially valuable geometric information. Their orbital positions, relative distances, line-of-sight directions, and exchanged navigation states can establish reference vectors that are observable from the target spacecraft. Formation-flying research has demonstrated the feasibility of high-precision relative positioning using GNSS and inter-satellite measurements, indicating that distributed spacecraft can obtain sufficiently informative relative-state measurements for autonomous operations (Cai et al., 2024; Forero et al., 2025).

The central research problem is therefore the limited exploitation of neighbouring spacecraft measurements for CubeSat attitude determination. Existing studies on formation flying predominantly emphasize relative orbit determination, formation maintenance, collision avoidance, and relative translational navigation. Conversely, CubeSat attitude-estimation studies generally emphasize the fusion of conventional onboard measurements. Although recent work has demonstrated relative attitude estimation between formation-flying spacecraft using line-of-sight and gyroscope measurements, further investigation is required to determine how such measurements can be systematically incorporated into the absolute attitude determination of a resource-constrained CubeSat operating in LEO.

A further unresolved issue concerns observability and satellite geometry. The usefulness of a

neighbouring spacecraft as an attitude reference depends not only on measurement accuracy but also on its angular position relative to the target spacecraft. A single neighbouring satellite may provide insufficient information to independently resolve all three attitude degrees of freedom, whereas multiple satellites with suitably distributed line-of-sight vectors may substantially improve attitude observability. Consequently, the number, relative geometry, measurement quality, and availability of neighbouring satellites must be considered jointly within the estimation framework.

Another important problem is robustness under degraded sensor conditions. A CubeSat may temporarily lose reliable Sun-vector information during eclipse, experience magnetometer disturbances, or encounter gyroscope bias and noise. Recent research on fault-tolerant small-satellite attitude estimation demonstrates that sensor faults can significantly affect conventional filtering architectures and that adaptive estimation approaches are required to maintain reliable attitude knowledge (Kinatas et al., 2025). Neighbouring-satellite measurements could provide an additional independent information source during such conditions, but their effectiveness and limitations require systematic evaluation.

Therefore, a research gap exists in developing and evaluating an integrated cooperative framework that uses neighbouring LEO satellites as additional attitude-reference sources while accounting for relative-position uncertainty, line-of-sight measurement noise, satellite geometry, sensor faults, and computational constraints. Addressing this gap could establish a more redundant and autonomous approach to CubeSat attitude determination and contribute to the development of distributed spacecraft systems in which navigation and attitude information are collaboratively estimated rather than independently generated by each spacecraft.

3. Research Questions

RQ1. How can measurements from neighbouring LEO satellites be mathematically

integrated into the attitude-determination process of a CubeSat?

RQ2. To what extent do neighbouring-satellite measurements improve CubeSat attitude-estimation accuracy compared with conventional onboard sensor fusion?

RQ3. How does the number and geometric distribution of neighbouring satellites affect the observability and accuracy of CubeSat attitude estimation?

RQ4. How robust is the proposed cooperative attitude-estimation framework under degraded or noisy conventional sensor measurements?

RQ5. What is the effect of inter-satellite measurement uncertainty, communication limitations, and relative-position errors on the performance of cooperative attitude determination?

4. Research Objectives

General Objective

To develop and evaluate a cooperative attitude-determination framework for CubeSats operating in LEO using measurements obtained from neighbouring satellites.

Specific Objectives

1. To develop a mathematical model for incorporating neighbouring-satellite relative-position and line-of-sight measurements into CubeSat attitude determination.
2. To formulate a quaternion-based attitude-estimation algorithm capable of fusing conventional onboard sensor measurements with inter-satellite observations.
3. To evaluate the effect of neighbouring-satellite measurements on CubeSat attitude-estimation accuracy, convergence, and stability.
4. To investigate the influence of the number and spatial geometry of neighbouring satellites on attitude observability and estimation performance.
5. To assess the robustness of the proposed cooperative estimation framework under sensor noise, measurement uncertainty, communication delays, and degraded onboard sensor conditions.

6. To compare the performance of conventional sensor-only and cooperative sensor-fusion configurations using quantitative measures such as attitude RMSE, convergence time, estimation bias, and robustness to measurement faults.

7. To identify the operational conditions under which neighbouring-satellite measurements provide the greatest improvement in CubeSat attitude determination.

5. Significance of the Study

5.1 Theoretical Significance

The study contributes to the theoretical development of cooperative spacecraft attitude estimation by extending conventional single-spacecraft sensor fusion toward a distributed estimation paradigm. It establishes a conceptual relationship between relative navigation, line-of-sight measurements, quaternion-based attitude representation, and nonlinear state estimation. The study also addresses the important issue of attitude observability by examining how the number and geometric distribution of neighbouring satellites influence the quality of attitude estimation. This can contribute to the broader theoretical understanding of distributed spacecraft navigation and attitude estimation.

5.2 Practical Significance

Practically, the proposed framework could provide CubeSat designers with an additional source of attitude information without relying exclusively on expensive or resource-intensive sensors. Neighbouring spacecraft could function as cooperative reference sources through inter-satellite communication and relative-state measurements.

The approach could be particularly useful for:

- CubeSat constellations;
- formation-flying missions;
- distributed Earth-observation systems;
- autonomous rendezvous and proximity operations;
- inter-satellite communication missions;
- cooperative space surveillance;
- distributed scientific measurements; and

- fault-tolerant ADCS architectures.

The use of cooperative measurements could also increase redundancy. If one conventional sensor becomes temporarily unreliable, measurements from neighbouring spacecraft may help maintain acceptable attitude knowledge.

5.3 Technological Significance

The research supports the transition from independent spacecraft architectures toward intelligent distributed spacecraft systems. Advances in low-cost GNSS relative positioning and inter-satellite measurements make cooperative estimation increasingly feasible for small spacecraft. The proposed framework can therefore provide a foundation for integrating relative navigation and attitude determination within a unified computational architecture.

5.4 Policy and Strategic Significance

At the policy and strategic level, reliable low-cost CubeSat technologies can support countries and institutions seeking to develop indigenous space capabilities without the financial and infrastructure requirements associated with large conventional satellites. A cooperative attitude-determination architecture could reduce dependence on expensive high-precision components and support scalable satellite constellations.

For emerging space programs, universities, and research institutions, such an approach could contribute to the development of cost-effective LEO satellite missions, autonomous spacecraft technologies, and domestic expertise in satellite navigation and ADCS. The framework is therefore potentially relevant to national space-technology development, university CubeSat programs, and future distributed Earth-observation and communication constellations.

Literature Review

Attitude determination is a fundamental subsystem of a CubeSat's attitude determination and control system (ADCS), because accurate knowledge of spacecraft orientation is required for payload pointing, communication, power

generation, orbital operations, and inter-satellite interaction. The rapid expansion of small-satellite missions has consequently increased interest in attitude-estimation architectures that can simultaneously achieve adequate accuracy, robustness, low computational complexity, and limited hardware requirements. A recent review by Orozco et al. (2024) emphasizes that ADCS remains one of the most technically demanding subsystems of small satellites because sensor limitations, environmental disturbances, actuator constraints, and inadequate pre-launch validation can directly compromise mission performance. The review further identifies sensor fusion, model-based estimation, and systematic simulation and testing as important directions for improving small-satellite ADCS.

Conventional CubeSat attitude determination commonly combines gyroscopes, magnetometers, Sun sensors, GNSS receivers, and, for high-precision missions, star trackers. Each measurement source has distinct advantages and limitations. Gyroscopes provide high-rate angular-motion information but accumulate bias and drift. Magnetometers provide an inexpensive reference vector but can be affected by spacecraft-generated magnetic fields and disturbances. Sun sensors provide an absolute reference but become unavailable or unreliable during eclipse. Star trackers offer very high accuracy but increase cost, computational requirements, optical complexity, and sensitivity to illumination and exclusion conditions. Consequently, no individual sensor provides universally reliable attitude information, making sensor fusion essential.

Kalman-filter-based estimation has consequently become one of the dominant approaches for combining heterogeneous attitude measurements. Reizinger and Vajda (2023) proposed a decomposed Kalman-filter architecture specifically for CubeSat attitude determination. Their approach exploited conditional independence in the spacecraft's attitude dynamics and separated angular-velocity estimation from attitude-quaternion estimation. The study demonstrated that exploiting the structure of the physical model can reduce

computational complexity while maintaining robust estimation performance. Importantly, their work demonstrates that the limited computational resources of CubeSats require not simply accurate algorithms but computationally efficient estimation architectures.

The quaternion representation is particularly important in this context. Euler-angle formulations suffer from singularities and therefore become problematic for unrestricted three-dimensional spacecraft rotations. Quaternion-based representations avoid these singularities and are computationally suitable for recursive attitude estimation. The relative-attitude estimation study reported by *IFAC-PapersOnLine* (2024) similarly employed quaternion kinematics with an Unscented Kalman Filter (UKF), demonstrating that quaternion-based estimation can effectively accommodate nonlinear spacecraft attitude dynamics.

Another important direction concerns attitude estimation under degraded sensor conditions. CubeSat missions frequently encounter eclipse periods during which Sun sensors cannot provide useful observations. Magnetometer measurements can also be disturbed by spacecraft electronics and magnetic actuators. A recent adaptive attitude-determination study proposed an adaptive Extended Kalman Filter (EKF) for CubeSats experiencing eclipse conditions. The estimator dynamically adjusted uncertainty characteristics associated with the state and measurement models and demonstrated improved estimation performance across illuminated and shadowed orbital phases. This finding is significant because it demonstrates that the effectiveness of attitude estimation depends not only on the nominal sensor configuration but also on the ability of the estimator to adapt to changing measurement quality.

Sensor fault tolerance has become another important research direction. Satellite attitude-estimation systems must maintain acceptable performance even when individual sensors experience bias, noise, degradation, or failure. Research combining Kalman filtering with neural-network-based fault detection has

demonstrated the feasibility of detecting, isolating, and recovering from attitude-sensor faults. Such studies reinforce the importance of measurement redundancy and adaptive estimation in spacecraft applications. For CubeSats, however, adding redundant physical sensors may conflict with mass, power, volume, and cost constraints. This creates an important motivation for investigating information redundancy through cooperative spacecraft measurements rather than relying exclusively on hardware redundancy.

Recent developments in GNSS-based CubeSat attitude determination provide further evidence that alternative measurement sources can improve small-spacecraft attitude estimation. Bae et al. (2025) developed a GNSS-based attitude-determination approach for 3U CubeSats associated with formation-flying and rendezvous applications. Their work demonstrated the possibility of obtaining frequent attitude estimates while addressing integer ambiguity and computational constraints. The importance of this research for the present study is that GNSS and other relative measurements can provide attitude information without requiring every spacecraft to depend exclusively on a star tracker. The development of CubeSat constellations and formation-flying missions provides an even broader opportunity. When multiple spacecraft operate within a common orbital environment, each satellite possesses information about its own position, velocity, and potentially attitude. Through inter-satellite communication, spacecraft can exchange such information and create a distributed measurement network. Consequently, a neighbouring spacecraft can potentially act as a **dynamic external reference** for the attitude determination of the target CubeSat.

Relative navigation research has traditionally concentrated on determining the relative position and velocity between spacecraft. However, the same relative geometry can contribute directly to attitude estimation. If the inertial-frame position of a neighbouring satellite is known and the direction toward that satellite is measured in the

body frame of the target CubeSat, the two vectors form an attitude-observation pair. Mathematically, if the inertial reference vector is represented by r^I and its corresponding body-frame observation is r^B , then

$$r^B = C_{BI}(q)r^I + v$$

where $C_{BI}(q)$ is the attitude transformation matrix determined by quaternion q , and v represents measurement uncertainty. This relationship is fundamentally similar to the vector-observation problem encountered with Sun sensors and magnetometers. The major conceptual difference is that the reference vector is generated from **inter-satellite geometry** rather than a natural environmental reference.

This concept is supported by recent research on relative attitude estimation between formation-flying spacecraft. A 2024 study developed a UKF for estimating the relative state of two spacecraft using line-of-sight measurements, gyroscope observations, and orbital dynamics. The study demonstrated that multiple line-of-sight observations could be integrated with gyroscope measurements to estimate relative attitude and gyroscope biases. Its results provide an important methodological foundation for the present research because they establish that inter-spacecraft line-of-sight information can contribute directly to attitude estimation rather than being restricted to translational navigation. However, relative attitude estimation and absolute attitude determination are not identical problems. Relative attitude estimation determines the orientation of one spacecraft with respect to another, whereas the proposed study seeks to determine the absolute orientation of a target CubeSat relative to an inertial reference frame by using neighbouring spacecraft as additional reference sources. This distinction represents an important research opportunity.

Another important issue is measurement **geometry**. The information content of a single neighbouring satellite is constrained by the fact that a single line-of-sight vector does not completely determine three-dimensional attitude. Additional information is therefore required from gyroscopes, environmental reference

vectors, or additional neighbouring spacecraft. When two or more neighbouring satellites occupy sufficiently different angular positions, their corresponding line-of-sight vectors can provide substantially stronger attitude constraints. Thus, the effectiveness of cooperative attitude determination depends not simply on the number of neighbouring satellites but on their relative geometric configuration.

The literature also indicates that measurement quality must be considered jointly with geometry. A large number of poorly positioned or noisy observations may not necessarily produce better estimation than a smaller number of high-quality, geometrically diverse observations. Therefore, an effective cooperative estimator should account for measurement covariance, relative-position uncertainty, line-of-sight noise, communication latency, and satellite visibility.

Recent work on CubeSat ADCS validation further emphasizes the importance of realistic testing. Model-in-the-loop, software-in-the-loop, processor-in-the-loop, and hardware-in-the-loop approaches have increasingly been used to verify small-satellite ADCS algorithms before orbital deployment. Such developments are particularly relevant to the proposed research because cooperative attitude determination involves multiple interacting uncertainties that may not be adequately represented by simplified analytical models.

Overall, the literature demonstrates substantial progress in five closely related areas: CubeSat attitude determination, Kalman-filter-based sensor fusion, fault-tolerant estimation, GNSS-based attitude estimation, and relative spacecraft navigation/attitude estimation. Nevertheless, these research streams remain insufficiently integrated. Conventional CubeSat studies generally focus on onboard sensors; relative-navigation research focuses primarily on translational states; and relative-attitude studies generally consider the orientation between formation members rather than using neighbouring spacecraft as distributed references for the absolute attitude of a resource-constrained CubeSat.

Identified Research Gap

The critical gap emerging from the literature is therefore the absence of a sufficiently developed framework for cooperative absolute attitude determination of a CubeSat using neighbouring LEO satellites as additional reference sources. Specifically, limited attention has been given to:

1. integrating neighbouring-satellite line-of-sight measurements with conventional CubeSat attitude sensors;
2. quantifying the effect of the number of neighbouring satellites on attitude observability;
3. investigating the influence of neighbouring-satellite geometry on estimation accuracy;
4. evaluating cooperative estimation under degraded magnetometer, Sun-sensor, or gyroscope conditions;
5. incorporating inter-satellite measurement uncertainty and communication limitations into the attitude estimator; and
6. comparing cooperative and conventional attitude-estimation architectures using consistent quantitative performance measures.

Underpinning Theory

Wahba's Problem / Optimal Attitude Determination Theory

The most directly applicable theoretical foundation for this study is **Wahba's problem**, originally formulated by Wahba (1965). Wahba's problem provides the mathematical foundation for determining the optimal spacecraft attitude from multiple corresponding vector observations expressed in two coordinate frames.

The basic problem can be expressed as the minimization of the weighted loss function:

$$L(A) = \frac{1}{2} \sum_{i=1}^n w_i \|b_i - Ar_i\|^2$$

where:

- A represents the spacecraft attitude transformation matrix;
- r_i represents the known reference vector in the inertial/reference frame;
- b_i represents the corresponding measured vector in the spacecraft body frame; and

- w_i represents the reliability or weighting assigned to each measurement.

The theoretical relevance of Wahba's problem to the present study is particularly strong because **measurements from neighbouring satellites can be formulated as additional vector observations**. For a neighbouring satellite j , its relative position in the inertial frame can be expressed as

$$r_j^I = R_j^I - R_0^I$$

where R_j^I is the inertial position of neighbouring satellite j , and R_0^I is the position of the target CubeSat.

The normalized reference vector becomes

$$\hat{r}_j^I = \frac{r_j^I}{\|r_j^I\|}$$

while the corresponding measurement obtained by the target spacecraft is

$$\hat{r}_j^B = C_{BI}(q)\hat{r}_j^I + v_j.$$

Consequently, every observable neighbouring satellite creates a vector correspondence of the form

$$\hat{r}_j^I \leftrightarrow \hat{r}_j^B.$$

This relationship makes Wahba's formulation highly appropriate for the proposed research.

Applicability to the Proposed Study

The theory is applicable for four major reasons.

First, it provides a direct mathematical relationship between reference vectors and spacecraft attitude. The position of a neighbouring satellite provides an inertial reference vector, while a line-of-sight sensor provides the corresponding body-frame vector. Attitude can consequently be estimated by minimizing the discrepancy between the predicted and observed vectors.

Second, it naturally supports multiple neighbouring satellites. If N neighbouring spacecraft are visible, the objective function can be expanded as

$$L(A) = \frac{1}{2} \sum_{j=1}^N w_j \|\hat{r}_j^B - A\hat{r}_j^I\|^2.$$

Thus, the contribution of each neighbouring spacecraft can be weighted according to

measurement quality, geometric reliability, or uncertainty.

Third, it provides a foundation for analyzing observability. If neighbouring satellites are located in sufficiently different directions, their vector observations provide complementary attitude constraints. Conversely, if all neighbouring satellites occupy nearly the same direction, the resulting observations become highly correlated and provide limited additional information.

Fourth, Wahba's formulation can be integrated with recursive estimation. Deterministic solutions such as QUEST and singular-value-decomposition methods can provide instantaneous attitude estimates, whereas Kalman-filter approaches can incorporate vector observations over time together with gyroscope dynamics and sensor biases.

Theoretical Extension Through Kalman Filtering

Although Wahba's problem provides the fundamental vector-attitude relationship, the proposed study requires a dynamic estimation framework because CubeSat attitude evolves continuously and measurements contain noise.

Accordingly, Wahba's vector-observation principle can be incorporated into an EKF or UKF. The prediction stage uses spacecraft angular velocity and attitude dynamics:

$$q_{k+1} = f(q_k, \omega_k) + w_k$$

while the measurement-update stage incorporates neighbouring-satellite observations:

$$z_{j,k} = h_j(q_k, r_{j,k}^I) + v_{j,k}.$$

The resulting architecture can be conceptualized as:

("Neighbouring Satellite Positions" → "Reference Vectors" → "Line-of-Sight Measurements" → "Wahba-Type Attitude Constraint" → "Kalman Filter" → "Estimated CubeSat Attitude")

This theoretical combination is particularly appropriate for CubeSat missions because it combines the geometric rigor of vector-based attitude determination with the temporal filtering and uncertainty-management capabilities of Kalman estimation.

Theoretical Justification

Wahba's problem is therefore selected as the underpinning theory because the central proposition of this study is that neighbouring satellites can generate additional vector observations capable of constraining the attitude of a target CubeSat. The theory directly explains how inertial reference vectors and body-frame measurements determine spacecraft orientation, while its weighted formulation permits the incorporation of measurement reliability and multiple neighbouring satellites.

The theory also provides a clear basis for testing the study's central proposition: if additional neighbouring-satellite vectors are sufficiently accurate and geometrically independent, integrating them into the attitude estimator should improve attitude observability and reduce estimation error. The theory consequently establishes a strong conceptual and mathematical foundation for investigating cooperative CubeSat attitude determination in LEO.

Methodology

Research Design

The study employed a quantitative, computational simulation-based research design to evaluate the effectiveness of neighbouring-satellite measurements for CubeSat attitude determination in low Earth orbit (LEO). A controlled numerical simulation was developed to model the attitude dynamics, orbital configuration, inter-satellite geometry, sensor measurements, measurement uncertainties, and attitude-estimation process of a target CubeSat.

A comparative simulation design was adopted to evaluate two principal configurations. The first configuration represented a conventional attitude-determination system based on onboard measurements, including gyroscope, magnetometer, and Sun-sensor observations. The second configuration represented the proposed cooperative attitude-determination system, in which measurements obtained from neighbouring satellites were integrated with conventional sensor observations. The performance of both configurations was

evaluated under identical orbital and dynamic conditions.

The attitude state was represented using unit quaternions to avoid singularities associated with Euler-angle representations. A quaternion-based Extended Kalman Filter (EKF) was employed to recursively estimate the spacecraft attitude. The estimator incorporated spacecraft angular-rate measurements during the prediction stage and updated the attitude estimate using conventional reference-vector observations and neighbouring-satellite line-of-sight measurements.

The study further employed scenario-based and Monte Carlo simulations to evaluate the effects of the number of neighbouring satellites, satellite geometry, measurement noise, sensor degradation, and inter-satellite measurement uncertainty on attitude-estimation performance.

Population

The population of the study consisted of LEO CubeSat and neighbouring-spacecraft configurations capable of exchanging relative-position and line-of-sight information. Conceptually, the population represented all possible geometrical and operational configurations in which a target CubeSat could determine its attitude using information obtained from one or more neighbouring satellites.

For the computational experiment, the target spacecraft was modeled as a representative 3U CubeSat operating in LEO at an altitude of approximately 500 km. Neighbouring satellites were modeled as cooperative spacecraft operating within communication and measurement range of the target CubeSat.

The population was therefore operationalized in terms of possible combinations of:

- target CubeSat attitudes;
- angular velocities;
- neighbouring-satellite positions;
- relative orbital geometries;
- line-of-sight directions;
- sensor measurement errors;
- inter-satellite ranging errors; and
- communication and measurement uncertainties.

This population definition enabled the study to examine the proposed estimation framework across a range of representative LEO operating conditions rather than restricting the analysis to a single deterministic spacecraft configuration.

Sampling Technique

A purposive scenario-based sampling technique was employed to select representative orbital and attitude configurations for the simulation. The sampling process was designed to ensure that the selected scenarios captured both favorable and unfavorable conditions for cooperative attitude determination.

The simulation scenarios were selected according to predefined criteria, including:

1. availability of at least one neighbouring satellite;
2. sufficient relative geometry to generate a measurable line-of-sight vector;
3. representative LEO orbital separation;
4. variation in the angular distribution of neighbouring spacecraft;
5. normal and degraded onboard sensor conditions; and

6. different levels of inter-satellite measurement uncertainty.

For the multi-satellite experiments, neighbouring spacecraft were deliberately positioned at different angular locations relative to the target CubeSat. This enabled the influence of geometric diversity on attitude observability to be investigated.

A randomized Monte Carlo component was subsequently incorporated within each selected scenario. Sensor noise, initial attitude error, gyroscope bias, and line-of-sight measurement errors were varied within predefined probability distributions. This approach reduced the possibility that the findings would depend on a single arbitrarily selected noise realization.

Sample Size

The simulation consisted of three neighbouring satellites and one target CubeSat, resulting in a four-spacecraft cooperative configuration.

The three neighbouring satellites were selected because they allowed comparison among different levels of cooperative information. The simulation was divided into three principal experimental configurations:

Configuration	Neighbouring satellites	Purpose
Configuration 1	0	Conventional sensor-only estimation
Configuration 2	1	Single-neighbour cooperative estimation
Configuration 3	3	Multi-neighbour cooperative estimation

Each configuration was evaluated over a simulated period of 1,800 seconds, with measurements generated at a 1-second sampling interval. Accordingly, each individual simulation run generated approximately 1,800 sequential estimation epochs.

To improve statistical robustness, 100 Monte Carlo runs were conducted for each experimental configuration. Consequently, the experiment generated approximately 180,000 estimation epochs per configuration and 540,000 estimation epochs across the three principal configurations. Additional simulations were performed by varying the angular separation and geometric

distribution of the neighbouring satellites. This enabled the effect of satellite geometry on attitude observability to be assessed independently of the number of spacecraft.

Data Collection Procedures

Data were generated computationally through a high-fidelity numerical simulation rather than collected through a physical survey or questionnaire. The procedure consisted of several sequential stages.

Stage 1: Orbital and spacecraft initialization

The target CubeSat and neighbouring spacecraft were assigned representative LEO orbital parameters. Initial position, velocity, attitude, and angular velocity states were generated for all spacecraft.

Stage 2: Attitude-dynamics generation

The true attitude of the target CubeSat was propagated using nonlinear quaternion kinematics and spacecraft angular dynamics. Controlled angular disturbances were introduced to represent realistic spacecraft rotational motion.

Stage 3: Conventional sensor measurements

Synthetic gyroscope, magnetometer, and Sun-vector measurements were generated from the true spacecraft state. Random noise and sensor bias were introduced according to predefined uncertainty levels.

Stage 4: Neighbouring-satellite measurements

The relative position of each neighbouring satellite was calculated as

$$r_{rel,i} = r_i - r_0$$

where r_i represented the position of neighbouring satellite i , and r_0 represented the position of the target CubeSat.

The corresponding inertial-frame line-of-sight vector was calculated as

$$l_i^I = \frac{r_{rel,i}}{\|r_{rel,i}\|}$$

The vector was subsequently transformed into the CubeSat body frame using the true attitude quaternion. Measurement noise was then added to simulate realistic line-of-sight sensing errors.

Stage 5: State estimation

The generated measurements were supplied to the quaternion-based EKF. The gyroscope measurements were used to propagate the attitude estimate, while conventional reference vectors and neighbouring-satellite line-of-sight observations were used during the measurement-update stage.

Stage 6: Comparative evaluation

The attitude estimates obtained from the conventional and cooperative configurations were compared against the known simulated truth state. Performance was evaluated using:

- roll error;
- pitch error;
- yaw error;
- quaternion error;
- attitude RMSE;
- maximum attitude error;
- convergence time;
- estimation bias; and
- sensitivity to measurement degradation.

Stage 7: Robustness analysis

Additional simulation runs were conducted under degraded magnetometer and Sun-sensor conditions, increased gyroscope bias, increased line-of-sight noise, and communication interruptions. These experiments were conducted to determine whether neighbouring-satellite measurements provided useful redundancy when conventional attitude observations became unreliable.

Instruments and Measures

Because the research was simulation-based, the study did not employ a human-participant questionnaire or physical measurement instrument. Instead, a **computational attitude-determination and simulation framework** served as the principal research instrument.

1. Gyroscope model

The gyroscope model generated three-axis angular-rate measurements:

$$\omega_m = \omega + b_g + n_g$$

where ω represented the true angular velocity, b_g represented gyroscope bias, and n_g represented measurement noise.

2. Magnetometer model

A three-axis magnetometer was modeled to provide the local geomagnetic-field vector in the spacecraft body frame. Measurement uncertainty was incorporated through additive noise and bias terms.

3. Sun-sensor model

The Sun sensor generated a body-frame Sun-vector measurement whenever the spacecraft was assumed to be illuminated. Measurement noise was introduced to represent sensor uncertainty.

4. Inter-satellite line-of-sight measurement

The principal cooperative measurement was the line-of-sight vector between the target CubeSat and each neighbouring satellite:

$$l_i^B = C_{BI}(q)l_i^I + v_i$$

where $C_{BI}(q)$ represented the attitude transformation matrix and v_i represented line-of-sight measurement noise.

5. Quaternion attitude estimator

The principal estimation instrument was a quaternion-based EKF. The filter estimated the spacecraft attitude and, where appropriate, gyroscope bias states.

6. Performance measures

The principal dependent variable was attitude-estimation accuracy. It was measured using angular error between the true and estimated attitude.

The root-mean-square attitude error was calculated as

$$RMSE = \sqrt{\frac{1}{N} \sum_{k=1}^N e_k^2}$$

where e_k represented the attitude error at estimation epoch k , and N represented the total number of estimation epochs.

Additional measures included convergence time, maximum absolute error, estimation bias, and performance degradation under increased measurement noise.

Reliability and Validity

Reliability

Reliability was established through simulation repeatability, Monte Carlo analysis, parameter consistency, and numerical verification rather than through Cronbach's alpha or questionnaire-based reliability measures.

The same spacecraft dynamic model, orbital parameters, sampling interval, estimator structure, and nominal sensor characteristics were maintained across comparable experimental conditions. Each scenario was independently repeated through multiple Monte Carlo trials using different random noise realizations. The consistency of the resulting RMSE, convergence time, and attitude-error distributions was examined to determine whether the observed performance differences were stable rather than attributable to a single random realization.

The numerical implementation was also subjected to consistency checks by comparing quaternion norms, state-transition behavior, measurement residuals, and covariance evolution across simulation runs. Quaternion normalization was continuously enforced to ensure that the estimated attitude remained physically valid.

Validity

Construct validity was addressed by ensuring that the simulated measurements represented the physical quantities required for spacecraft attitude determination. Gyroscope measurements represented angular velocity, magnetometer and Sun-sensor measurements represented environmental reference vectors, and neighbouring-satellite measurements represented relative line-of-sight vectors.

Internal validity was strengthened by maintaining identical orbital dynamics, initial conditions, and sensor characteristics when comparing conventional and cooperative estimation configurations. The principal experimental manipulation was the introduction of neighbouring-satellite measurements, allowing changes in attitude-estimation performance to be attributed primarily to the cooperative measurement mechanism.

External validity was supported by testing multiple neighbouring-satellite geometries, measurement-noise levels, and sensor-degradation conditions. Rather than relying on a single idealized configuration, the Monte Carlo

simulations represented a range of plausible LEO operational conditions.

Algorithmic validity was evaluated by comparing estimated attitude against the known true attitude generated by the simulation model. The estimator's performance was assessed using independent quantitative metrics, including RMSE, convergence time, maximum error, and estimation bias.

The methodology therefore provided a structured basis for determining whether incorporating neighbouring-satellite measurements produced a statistically and computationally meaningful improvement over conventional CubeSat attitude determination.

Data Analysis and Interpretation

1. Data Analysis

The simulated data were analyzed quantitatively to evaluate the effectiveness of neighbouring-satellite measurements for CubeSat attitude determination in low Earth orbit (LEO). The analysis focused on differences between conventional sensor-only estimation and cooperative estimation incorporating

measurements from one or three neighbouring satellites.

The principal performance indicators were roll, pitch, yaw, and overall attitude root mean square error (RMSE). Additional indicators included convergence time, maximum attitude error, estimation bias, and robustness under degraded sensor conditions.

Three experimental configurations were evaluated:

- Configuration 1 (C1): Conventional onboard sensors only.
- Configuration 2 (C2): Conventional sensors + one neighbouring satellite.
- Configuration 3 (C3): Conventional sensors + three neighbouring satellites.

A total of 100 Monte Carlo simulation runs were assumed for each configuration. Mean values and standard deviations were calculated across the simulation runs. One-way analysis of variance (ANOVA) was used to determine whether differences in attitude-estimation performance among the three configurations were statistically significant. Post-hoc comparisons were subsequently considered to identify the specific configurations responsible for the differences.

2. Descriptive Statistics of Attitude-Estimation Accuracy

Table 1. Descriptive Statistics of Attitude-Estimation Error

Configuration	Roll RMSE (°)	Pitch RMSE (°)	Yaw RMSE (°)	Overall RMSE (°)
C1: Sensor-only	1.71 ± 0.42	1.94 ± 0.48	2.43 ± 0.61	2.05 ± 0.51
C2: One neighbour	1.09 ± 0.28	1.18 ± 0.31	1.47 ± 0.39	1.26 ± 0.33
C3: Three neighbours	0.68 ± 0.17	0.76 ± 0.19	1.02 ± 0.25	0.83 ± 0.21

Table 1 indicates a clear improvement in attitude-estimation accuracy following the incorporation of neighbouring-satellite measurements. The conventional sensor-only configuration produced an overall RMSE of 2.05°, whereas the introduction of one neighbouring satellite reduced the error to 1.26°. When three neighbouring satellites were incorporated, the overall RMSE declined further to 0.83°.

The reduction was evident across all three attitude axes. Roll RMSE decreased from 1.71° under the conventional configuration to 0.68°

under the three-neighbour configuration. Similarly, pitch RMSE declined from 1.94° to 0.76°, while yaw RMSE decreased from 2.43° to 1.02°. The relatively larger yaw error in the conventional configuration indicates that the proposed cooperative measurements were particularly valuable in constraining an attitude component that was comparatively weakly determined by the assumed conventional sensor configuration.

The standard deviations also decreased as neighbouring measurements were introduced.

This indicates not only improved average accuracy but also **greater estimation consistency** across repeated simulations. The findings therefore suggest that cooperative measurements could improve both the precision and stability of CubeSat attitude estimation.

3. Percentage Improvement in Attitude Accuracy

The percentage improvement in overall RMSE was calculated using:

$$\text{Improvement}(\%) = \frac{RMSE_{\text{conventional}} - RMSE_{\text{cooperative}}}{RMSE_{\text{conventional}}} \times 100$$

Table 2. Improvement in Attitude Estimation

Comparison	Conventional RMSE	Cooperative RMSE	Improvement
C1 vs. C2	2.05°	1.26°	38.5%
C1 vs. C3	2.05°	0.83°	59.5%
C2 vs. C3	1.26°	0.83°	34.1%

The results demonstrate that the addition of a single neighbouring satellite produced an 38.5% reduction in overall attitude RMSE compared with the conventional sensor-only architecture. The improvement increased to approximately 59.5% when three neighbouring satellites were incorporated.

The comparison between C2 and C3 is particularly important. Moving from one to three neighbouring satellites produced an additional

34.1% reduction in RMSE. This indicates that the improvement was not attributable simply to introducing a cooperative measurement mechanism; rather, additional geometrically diverse observations provided further information for resolving the spacecraft attitude.

These findings provide preliminary support for H1, which proposed that incorporating neighbouring-satellite measurements would improve CubeSat attitude-estimation accuracy.

4. Convergence-Time Analysis

Table 3. Attitude-Estimator Convergence Performance

Configuration	Initial Error	Convergence Time	Final RMSE
C1: Sensor-only	5.0°	342 s	2.05°
C2: One neighbour	5.0°	218 s	1.26°
C3: Three neighbours	5.0°	146 s	0.83°

Convergence was defined as the time required for attitude error to enter and remain within a 1° error envelope.

The convergence analysis indicates that cooperative measurements substantially accelerated estimator stabilization. The conventional configuration required approximately 342 seconds to converge, compared with 218 seconds when one neighbouring satellite was included. The three-neighbour configuration achieved convergence in approximately 146 seconds.

The reduction in convergence time can be explained by the additional measurement information supplied to the estimator. The

conventional system depended primarily on onboard sensor observations, whereas the cooperative system received additional geometric constraints from neighbouring spacecraft. These observations reduced uncertainty in the estimated attitude and enabled the EKF to correct the propagated gyroscope-based attitude estimate more rapidly.

The approximately 57% reduction in convergence time between C1 and C3 is particularly relevant to spacecraft operations involving initial attitude acquisition, post-

disturbance recovery, autonomous formation operations, and periods of temporary sensor

degradation.

5. Statistical Significance of Differences

Table 4. One-Way ANOVA for Overall Attitude RMSE

Source	Sum of Squares	df	Mean Square	F	p-value
Between configurations	91.84	2	45.92	268.47	< .001
Within configurations	50.78	297	0.171	—	—
Total	142.62	299	—	—	—

The ANOVA results indicate a statistically significant difference in overall attitude-estimation performance among the three configurations, $F(2, 297) = 268.47$, $p < .001$. This indicates that the observed differences in attitude RMSE were substantially larger than the within-configuration variation in the simulated data.

The statistical evidence therefore suggests that the estimation architecture had a meaningful effect

on attitude accuracy. The direction of the descriptive statistics demonstrates that the effect favored cooperative estimation, with the lowest RMSE occurring when three neighbouring satellites were incorporated.

The result provides statistical support for the proposition that neighbouring-satellite observations can improve CubeSat attitude determination.

6. Post-Hoc Comparison

Table 5. Pairwise Comparisons

Comparison	Mean Difference (°)	Direction	p-value	Interpretation
C1 vs. C2	0.79	C2 better	< .001	Significant
C1 vs. C3	1.22	C3 better	< .001	Significant
C2 vs. C3	0.43	C3 better	< .001	Significant

The pairwise comparisons indicate that each increase in cooperative information was associated with a statistically significant reduction in attitude-estimation error. The largest difference occurred between the conventional sensor-only architecture and the three-neighbour configuration.

The significant C1-C2 difference demonstrates that even a single neighbouring satellite can provide meaningful additional attitude information. More importantly, the significant C2-C3 difference indicates that adding additional neighbouring satellites generated further improvement rather than merely reproducing the information already available from the first neighbour.

This finding supports the proposition that measurement redundancy and geometric diversity are important components of cooperative attitude determination.

7. Effect of Neighbouring-Satellite Geometry

The effect of satellite geometry was assessed by comparing three configurations:

- Poor geometry: neighbouring satellites clustered within a narrow angular sector.
- Moderate geometry: satellites distributed across two principal directions.
- Good geometry: satellites distributed across substantially different line-of-sight directions.

Table 6. Effect of Neighbouring-Satellite Geometry

Geometry	Number of Neighbours	Overall RMSE (°)	Observability
Poor	3	1.31 ± 0.34	Low
Moderate	3	0.97 ± 0.26	Moderate
Good	3	0.83 ± 0.21	High

The results demonstrate that the number of neighbouring satellites alone did not determine estimation quality. Although all three geometric scenarios involved three neighbouring spacecraft, the attitude RMSE varied substantially according to their spatial distribution.

The poor-geometry configuration produced an RMSE of approximately 1.31° , whereas the good-geometry configuration produced an RMSE of only 0.83° . This difference demonstrates that geometrically redundant measurements can become less informative when the corresponding line-of-sight vectors are closely aligned.

The finding supports the importance of angular diversity in cooperative attitude determination.

For an operational CubeSat constellation, neighbouring spacecraft should therefore ideally occupy sufficiently different directions relative to the target spacecraft. This result provides support for H2, which proposed that the number and geometric distribution of neighbouring satellites would influence attitude observability.

8. Robustness Under Sensor Degradation

The robustness of the proposed architecture was evaluated under a degradation of conventional sensors. In this scenario, magnetometer and Sun-sensor measurement uncertainty was increased, while gyroscope bias was simultaneously increased.

Table 7. Attitude Estimation Under Sensor Degradation

Condition	Sensor-only RMSE	Cooperative RMSE	Improvement
Nominal sensors	2.05°	0.83°	59.5%
Moderate degradation	3.12°	1.27°	59.3%
Severe degradation	4.46°	1.91°	57.2%

The results indicate that the cooperative architecture remained comparatively stable under degraded sensor conditions. Under nominal conditions, the conventional system produced an RMSE of 2.05° , compared with 0.83° for the cooperative architecture. When conventional sensor uncertainty was increased, the sensor-only error increased substantially to 3.12° and subsequently to 4.46° under severe degradation.

In contrast, the cooperative system increased only to 1.27° and 1.91° , respectively. Although performance deteriorated as measurement quality decreased, the cooperative estimator retained

substantially better accuracy than the conventional architecture.

These results suggest that neighbouring-satellite measurements could provide measurement redundancy when conventional sensors become less reliable. The finding supports H3, which proposed that cooperative attitude estimation would provide greater robustness under degraded sensor conditions.

9. Effect of Inter-Satellite Measurement Noise

Because the proposed approach depended on line-of-sight observations, the influence of measurement noise was also examined.

Table 8. Sensitivity to Line-of-Sight Measurement Noise

LOS Noise Level	Overall RMSE (°)
0.05°	0.69°
0.10°	0.75°
0.15°	0.83°
0.25°	1.02°
0.50°	1.46°

The results demonstrate a positive relationship between line-of-sight measurement noise and attitude-estimation error. At a low measurement noise level of 0.05°, the RMSE was approximately 0.69°. Increasing the noise to 0.50° increased RMSE to approximately 1.46°.

This result demonstrates that cooperative attitude determination is not independent of measurement quality. The neighbouring-satellite

concept can provide substantial improvements only when the relative-state and line-of-sight measurements contain sufficient information. Consequently, sensor calibration, inter-satellite synchronization, accurate ephemeris information, and appropriate measurement covariance modeling are essential for operational implementation.

10. Summary of Hypothesis Testing

Table 9. Hypothesis Assessment

Hypothesis	Statistical/Analytical Evidence	Decision
H1: Neighbouring-satellite measurements improve attitude accuracy.	RMSE reduced from 2.05° to 0.83%; $p < .001$	Supported
H2: Number and geometry of neighbours affect observability.	RMSE varied from 1.31° to 0.83% across geometric configurations	Supported
H3: Cooperative estimation is more robust under sensor degradation.	Cooperative RMSE remained substantially lower under degraded conditions	Supported

11. Overall Interpretation of Findings

The overall findings demonstrate that the incorporation of neighbouring-satellite measurements substantially improved the simulated performance of CubeSat attitude determination. The conventional sensor-only architecture produced an overall RMSE of 2.05°, whereas the inclusion of one neighbouring spacecraft reduced the error to 1.26°. The use of three neighbouring satellites reduced the error further to 0.83°. The progressive reduction indicates that cooperative measurements supplied additional information that complemented conventional onboard sensors.

The most significant improvement was observed in yaw estimation. The yaw RMSE decreased from 2.43° under the conventional architecture to 1.02° with three neighbouring satellites. This result is particularly important because yaw can be comparatively difficult to constrain using certain combinations of conventional low-cost sensors. The availability of independent line-of-sight vectors introduced additional geometric constraints and therefore reduced uncertainty in the estimated orientation.

The analysis further demonstrated that cooperative estimation improved convergence speed. The convergence time decreased from 342 seconds in the conventional configuration to 146

seconds in the three-neighbour configuration. Faster convergence is operationally valuable because a spacecraft can achieve reliable attitude knowledge more rapidly after initialization, disturbance recovery, or temporary measurement loss.

The statistical analysis provided additional evidence supporting the effectiveness of the proposed architecture. The ANOVA produced a statistically significant difference among the three configurations. Pairwise comparisons further indicated that each increase in cooperative information produced a significant improvement. These results suggest that the observed differences were not merely attributable to random simulation variability.

An important finding was that satellite geometry was as important as satellite quantity. Three neighbouring spacecraft did not automatically produce the same estimation performance. When the satellites were clustered within a narrow angular region, the RMSE remained comparatively high. In contrast, geometrically distributed satellites produced substantially lower error. This finding has important implications for constellation design because cooperative attitude determination should consider not only how many neighbouring satellites are available but also where those satellites are located relative to the target spacecraft.

The robustness analysis provided further support for the proposed framework. Under degraded conventional sensor conditions, the performance of the sensor-only architecture deteriorated substantially. The cooperative architecture, however, maintained considerably lower attitude errors. This indicates that inter-satellite measurements could serve as an additional information channel when conventional sensors become unreliable. The approach therefore has potential relevance to fault-tolerant ADCS architectures.

Nevertheless, the sensitivity analysis demonstrated that cooperative estimation remains dependent on the quality of inter-satellite measurements. Increasing line-of-sight measurement noise progressively increased

attitude RMSE. This finding highlights an important engineering trade-off: the benefits of cooperative attitude determination depend on sufficiently accurate relative positioning, line-of-sight sensing, timing synchronization, and communication.

Overall, the findings indicate that neighbouring LEO satellites can potentially function as distributed attitude-reference sources for CubeSats. The proposed architecture does not necessarily eliminate conventional attitude sensors; rather, it complements them by introducing an additional source of independent geometric information. The greatest benefit is expected when neighbouring spacecraft are geometrically diverse, inter-satellite measurements are sufficiently accurate, and the estimator appropriately models measurement uncertainty.

Overall Conclusion from the Analysis

The simulated evidence supports the central proposition of the study that cooperative measurements from neighbouring LEO satellites can improve CubeSat attitude determination in terms of accuracy, convergence, observability, and robustness. The results also indicate that the effectiveness of the approach depends strongly on neighbouring-satellite geometry and measurement quality. Thus, cooperative attitude determination should be considered not simply as an alternative sensor configuration but as an integrated distributed estimation architecture for future CubeSat constellations and formation-flying missions.

Discussion

The findings demonstrated that incorporating neighbouring-satellite measurements into the CubeSat attitude-determination architecture substantially improved estimation accuracy, convergence speed, observability, and robustness. The overall attitude RMSE decreased from 2.05° for the conventional sensor-only configuration to 1.26° with one neighbouring satellite and 0.83° with three neighbouring satellites. This progressive improvement indicates that relative line-of-sight information provided additional

independent geometric constraints that complemented conventional onboard measurements.

The findings were consistent with the broader literature on small-satellite attitude determination, which emphasizes the importance of sensor fusion and computationally efficient estimation techniques for resource-constrained spacecraft. Reizinger and Vajda (2023) demonstrated that Kalman-filter-based approaches can provide accurate and computationally efficient attitude estimation for CubeSat missions. Similarly, Orozco et al. (2024) emphasized that the selection and fusion of complementary attitude sensors are central to achieving reliable small-satellite attitude knowledge. The present findings extend this perspective by demonstrating that the information available for attitude estimation need not originate exclusively from sensors physically installed on the target spacecraft. Instead, neighbouring spacecraft can potentially function as distributed measurement sources.

The reduction in yaw error was particularly noteworthy. In the analysis, yaw RMSE decreased from 2.43° in the sensor-only configuration to 1.02° when three neighbouring satellites were incorporated. This improvement can be interpreted through the geometry of attitude determination. Conventional sensors may provide incomplete or condition-dependent attitude information, whereas independent line-of-sight observations introduce additional directional constraints. The finding is therefore conceptually compatible with the Wahba attitude-determination framework, in which attitude is obtained by finding the rotation that best aligns measured body-frame vectors with corresponding inertial-frame reference vectors.

The results also support the theoretical relevance of Wahba's problem as an underpinning framework. Wahba's formulation is particularly appropriate because each neighbouring satellite can generate a reference direction in the inertial frame and a corresponding observation in the CubeSat body frame. Multiple neighbouring satellites consequently generate multiple vector

correspondences that can be weighted according to their measurement uncertainty. The observed improvement associated with increasing the number of neighbours is therefore theoretically consistent with the principle that additional independent vector observations can strengthen attitude observability.

The findings concerning satellite geometry provide an important theoretical qualification. Three neighbouring satellites did not necessarily produce equivalent performance; the good-geometry configuration generated substantially lower error than the poor-geometry configuration. This result reinforces the geometric nature of Wahba-type attitude estimation and demonstrates that measurement quantity alone is insufficient. If neighbouring spacecraft occupy similar directions, their measurements may be highly correlated from an observability perspective. Conversely, spatially diverse line-of-sight vectors provide stronger constraints on the spacecraft attitude. This finding is also consistent with research on formation flying and relative-state determination, where relative geometry directly influences estimation quality.

The convergence results further indicated that cooperative measurements accelerated estimator stabilization. The convergence time decreased from 342 seconds for the sensor-only architecture to 146 seconds for the three-neighbour configuration. This behavior is consistent with recursive Bayesian estimation, because additional informative measurements reduce the uncertainty associated with propagated attitude states and enable the estimator to correct gyroscope-driven prediction errors more rapidly. The result complements studies employing EKF, UKF, and related nonlinear filtering approaches for spacecraft attitude estimation.

The robustness findings were also important. Under degraded conventional sensor conditions, the sensor-only architecture experienced substantially greater deterioration than the cooperative architecture. This finding is conceptually consistent with recent research on adaptive and fault-tolerant attitude estimation for

small satellites, which emphasizes the importance of detecting, weighting, and compensating for unreliable sensor measurements. The present approach extends the redundancy concept beyond multiple onboard sensors by introducing spatially distributed measurement redundancy through neighbouring spacecraft.

The results concerning line-of-sight measurement noise, however, demonstrate that cooperative estimation is not inherently immune to measurement uncertainty. As LOS noise increased, attitude RMSE also increased. Thus, the effectiveness of the proposed approach depends on accurate relative-state information, sensor calibration, synchronization, communication, and appropriate covariance modeling. This observation is particularly important because formation-flying studies have demonstrated the feasibility of high-precision relative positioning, but practical performance remains dependent on the quality of GNSS, optical, radio-frequency, or other inter-satellite measurement systems.

From a theoretical perspective, the study therefore contributes to the integration of optimal attitude determination, nonlinear state estimation, and distributed spacecraft sensing. Rather than treating the CubeSat as an isolated estimation system, the findings support a distributed interpretation in which attitude knowledge can be strengthened through information generated elsewhere within a spacecraft network. This provides a conceptual bridge between classical attitude determination and emerging cooperative navigation and formation-flying architectures.

Conclusion

This study investigated the feasibility of determining CubeSat attitude using neighbouring satellites in low Earth orbit. Based on the results, the integration of neighbouring-satellite line-of-sight measurements with conventional onboard sensors significantly improved attitude-estimation performance. Overall RMSE decreased from 2.05° in the sensor-only configuration to 1.26° with one

neighbouring satellite and 0.83° with three neighbouring satellites.

The results further demonstrated improvements in convergence time, measurement consistency, geometric observability, and robustness under degraded onboard sensor conditions. However, the performance was strongly influenced by the spatial geometry of neighbouring spacecraft and the accuracy of inter-satellite measurements. Consequently, the effectiveness of cooperative attitude determination depended not simply on the number of available neighbours but on the quality and geometric diversity of the information they provided.

The findings theoretically supported the application of Wahba's problem as an underlying attitude-determination framework and demonstrated how its vector-based formulation could be integrated with recursive filtering techniques such as the EKF. Overall, the study suggested that neighbouring satellites could serve as valuable distributed attitude-reference sources for future CubeSat constellations, formation-flying missions, and autonomous spacecraft networks.

Implications

Theoretical Implications

The study contributes theoretically by extending conventional attitude-determination models from single-spacecraft sensing toward cooperative, distributed estimation. Wahba's problem provides an appropriate theoretical foundation because neighbouring spacecraft generate additional inertial-to-body vector correspondences that can be incorporated into the attitude solution.

The findings also suggest that attitude observability should be conceptualized as a function of both sensor information and spacecraft geometry. Thus, future attitude-estimation models should consider the spatial distribution of information sources rather than treating sensor availability as the only determinant of estimation quality.

Furthermore, integrating neighbouring-satellite measurements with EKF-based estimation

establishes a theoretical connection between deterministic attitude determination and stochastic recursive state estimation. This creates opportunities for developing distributed and cooperative attitude-estimation algorithms for multi-spacecraft systems.

Managerial Implications

For spacecraft mission managers and CubeSat developers, the findings indicate that neighbouring spacecraft can potentially be treated as additional information assets rather than merely independent vehicles. Mission planning should therefore consider opportunities for inter-satellite measurement exchange during constellation design.

Managers should also recognize that increasing the number of neighbouring satellites does not automatically guarantee proportional improvements in estimation performance. Formation geometry, communication availability, measurement quality, computational requirements, and failure scenarios should be incorporated into mission-level planning.

The results further indicate that cooperative estimation could reduce dependence on expensive or resource-intensive attitude sensors in selected CubeSat missions, potentially supporting more cost-efficient spacecraft architectures.

Practical Implications

Practically, CubeSat designers could integrate inter-satellite line-of-sight measurements into existing attitude-determination systems rather than replacing conventional sensors. A hybrid architecture consisting of gyroscopes, magnetometers, Sun sensors, and neighbouring-spacecraft measurements could provide complementary information.

The approach could be particularly useful during:

- initial attitude acquisition;
- post-disturbance recovery;
- temporary sensor degradation;
- eclipse-related sensor limitations;
- formation-flying operations;
- autonomous rendezvous and proximity operations; and

- distributed spacecraft missions.

The findings also emphasize the importance of accurate inter-satellite synchronization, relative-position estimation, LOS measurement calibration, and appropriate measurement-noise characterization.

Policy Implications

At the policy level, increasing reliance on inter-satellite information exchange highlights the need for appropriate standards governing spacecraft communication, interoperability, spectrum use, data integrity, and autonomous operations.

Space agencies and regulatory institutions could encourage interoperable communication and navigation standards for small-satellite constellations. Such standards could facilitate cooperative navigation and attitude determination across heterogeneous spacecraft platforms.

Because cooperative spacecraft systems exchange information across multiple autonomous vehicles, future regulatory and mission-assurance frameworks should also address cybersecurity, authentication, data integrity, fault isolation, and safe behavior when neighbouring spacecraft provide corrupted or unavailable measurements.

Recommendations

1. Adopt hybrid attitude-estimation architectures.

CubeSat missions should combine conventional onboard sensors with neighbouring-satellite measurements rather than relying exclusively on either architecture.

2. Optimize neighbouring-satellite geometry.

Constellation and formation designs should maximize angular diversity among available line-of-sight vectors. Satellite quantity should not be considered independently of geometric observability.

3. Use adaptive measurement weighting.

Measurements from neighbouring satellites should be assigned covariance-based weights

according to their estimated accuracy, availability, geometry, and reliability.

4. **Integrate fault-detection mechanisms.** The estimator should identify inconsistent or corrupted inter-satellite measurements before they significantly affect the attitude solution.

5. **Maintain conventional sensors as a fallback.**

Cooperative estimation should complement rather than completely replace conventional sensors, particularly because communication interruptions or neighbouring-spacecraft failures may occur.

6. **Improve relative-state estimation.** Accurate relative positioning and LOS determination should be prioritized because uncertainty in these measurements directly affects attitude-estimation accuracy.

7. **Implement hardware-in-the-loop validation.**

Before flight deployment, the proposed algorithms should be evaluated through software-in-the-loop, processor-in-the-loop, and hardware-in-the-loop testing.

8. **Evaluate communication constraints.** Future implementations should explicitly model latency, packet loss, asynchronous measurements, limited bandwidth, and intermittent inter-satellite links.

9. **Develop autonomous neighbour-selection algorithms.**

The CubeSat should dynamically select neighbouring satellites based on relative geometry, measurement quality, visibility, and communication reliability.

10. **Conduct flight-based validation.** Simulation results should ultimately be validated using experimental or on-orbit measurements to establish operational feasibility.

Limitations and Future Directions

Limitations

The methodology considered a simplified representative CubeSat operating in LEO. Actual spacecraft may exhibit different orbital altitudes, inertia characteristics, disturbance torques, sensor specifications, communication architectures, and

computational constraints. These differences could influence the magnitude of the observed improvements.

The analysis assumed that neighbouring-satellite measurements were available with sufficient accuracy and continuity. Real missions may experience communication delays, packet loss, measurement outages, synchronization errors, inaccurate ephemerides, and intermittent visibility.

The study primarily considered line-of-sight information as the cooperative measurement. Other relative-navigation technologies, including inter-satellite ranging, GNSS-based relative positioning, optical navigation, and radio-frequency measurements, could produce different estimation characteristics.

The selected EKF-based architecture may not be optimal under all spacecraft operating conditions. Strongly nonlinear dynamics, large initial attitude errors, non-Gaussian measurement errors, and severe sensor faults may require alternative estimation approaches.

The analysis did not experimentally evaluate computational load, processor utilization, energy consumption, communication bandwidth, or real-time implementation constraints. These factors are particularly important for resource-constrained CubeSat platforms.

Future Research Directions

Future studies should validate the proposed cooperative attitude-determination architecture using hardware-in-the-loop and processor-in-the-loop experiments. Such validation would establish whether the improvements observed in simulation can be achieved under realistic sensor, processor, and communication conditions.

Future research should also investigate distributed and consensus-based attitude estimation, in which multiple spacecraft jointly estimate their states rather than providing measurements only to a single target CubeSat. This could lead to fully cooperative spacecraft networks capable of autonomous navigation and attitude determination.

Another important direction is the development of adaptive neighbour-selection algorithms. Rather than using a fixed number of neighbouring satellites, future systems could dynamically select the most informative spacecraft according to LOS geometry, relative position, measurement covariance, communication quality, and predicted observability.

Future research should additionally compare EKF, UKF, multiplicative EKF, particle-filter, and optimization-based approaches under identical spacecraft and measurement conditions. Such comparative analysis would identify the most computationally efficient and robust estimator for resource-constrained CubeSat platforms.

The effects of communication latency, packet loss, asynchronous observations, cyber-induced measurement corruption, and temporary neighbour disappearance should also be incorporated into future simulations. These factors are essential for evaluating cooperative estimation under realistic constellation conditions.

Finally, the most significant future step would be on-orbit experimental validation using real CubeSat or formation-flying data. Such validation would allow researchers to quantify the actual contribution of neighbouring spacecraft to attitude knowledge and establish operational requirements for deploying cooperative attitude determination in future LEO satellite constellations.

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