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Master Attitude Controller for Modular Laser Communication Systems

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Abstract: Space-based free-space optical communication requires precisely coordinating the pointing of multiple subsystems. In order to manage the control interfaces and dynamics of evolving actuators and sensors, and their design limitations, a dedicated control unit has been developed and is presented in this work: the Master Attitude Controller. It facilitates integration of the satellite's attitude determination and control system with the optical communication payload. Additionally, it incorporates an on-board inertial measurement unit to enhance the accuracy of attitude knowledge during the acquisition phase. In the subsequent tracking phase, it uses control allocation to distribute the control effort among all effectors.

Keywords: free-space optical communications, acquisition and tracking, control allocation, attitude estimation, attitude determination and control, CubeSat

1. INTRODUCTION

Increasingly complex free-space optical communication (FSOC) missions in dynamic link scenarios on small satellites are leading to the development of multiple, employed actuator and sensor subsystems (Rödiger et al. (2025); Dresscher et al. (2019); Kramer et al. (2020); Krause et al. (2023)). The selection and combination of these subsystems depends on mission requirements, making modular components appealing. Each combination requires precise and robust fine-tuning of the attitude control algorithms, implicating high development and testing capacities. Additionally, companies or research institutes that develop the respective laser communication terminal (LCT) often source the satellite from third-party institutions. This means that numerous interfaces must be properly defined, and the requirements and limitations need to be understood on both ends.

A concept that actively counteracts these challenges is currently being developed for upcoming missions in the optical space infrared downlink system (OSIRIS) framework. This dedicated master attitude controller (MAC) unit is presented in this work. The approach involves aspects of a generalized concept of a central control unit, as well as the implementation of the necessary hardware. In this work, a high-level overview of the necessary components and considerations will be summarized, while references to detailed aspects are made where applicable.

The requirements for the proposed system can be derived from current state-of-the-art missions and available solutions on the market. Initially, during the acquisition phase, the attitude determination and control system (ADCS) has the most accurate information about the current attitude with respect to the optical link target. This attitude knowledge is crucial for improving the probability of successful link acquisition and reducing the mean acquisition time across all attempts (Rüddenklau and Schitter (2024)). Therefore, data can be transferred to the LCT, but the update rate is insufficient to compensate for pointing errors at the scan speed of the optical terminal. This raises the need for self-contained attitude sensors.

In the next phase, during optical tracking, the ADCS would benefit from the improved pointing knowledge provided by the LCT. However, such an interface is not currently available on commercial CubeSat buses, meaning that an implementation would require additional engineering work from the satellite manufacturer. To avoid this costly and time-consuming process, the MAC offers the advantage of integrating the ADCS into the control system at a higher level. Most satellite buses provide an input to offset the pointing reference used to determine the attitude error. This offers a simple solution for incorporating the pointing knowledge of the LCT into the satellite pointing system. All satellite limitations, such as sun avoidance, remain active, and since the LCT can deliver offsets at a rate higher than the attitude estimation update rate, potential sensor faults (e.g., star tracker lock loss during high-rate rotations) can be mitigated. This ensures the spacecraft stays within the field of regard (FOR) of the LCT (Rüddenklau et al. (2024)). Additionally, whenever the LCT loses its tracking lock (e.g., due to clouds), no mode switch of the ADCS is required, as the last command can be retained as an offset until the laser beacon is reacquired.

The paper is structured as follows: Section 2 discusses common attitude manipulation subsystems for a satellite-

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based optical link. It also presents strategies to enhance attitude knowledge during acquisition, as well as the controller architecture for multi-actuator, multi-sensor systems. Section 3 covers the implementation of the concept into the actual hardware, outlining the implications at the project level. Following that, the onboard peripherals and their calibration are described, along with considerations for a generic electrical interface and a dedicated communication protocol for inter-subsystem data transfer.

2. MASTER ATTITUDE CONTROL CONCEPT

The following section is dedicated to the concept of the proposed centralized control architecture, which incorporates multiple actuator and sensor subsystems. It explains how the attitude propagation capabilities and modular control approach can support and improve the acquisition and tracking phases of an optical link.

2.1 Laser Communication Subsystems

The use of FSOC systems on airborne or spaceborne platforms such as zeppelins, high-altitude platforms, airplanes, or satellites is advantageous, as they can cover large distances with minimal obstructions, thereby increasing the effective communication range. As a result, LCTs are commonly mounted on such host platforms, which can be used for body pointing to align the optical beam. This is particularly beneficial for satellites, as they can adjust their attitude largely independently of their orbital motion.

Satellites also provide the capability to host multiple LCTs, enabling inter-satellite links as well as connections with optical ground stations. A typical LCT comprises a coarse pointing assembly (CPA) to extend the pointing range and a fine pointing assembly (FPA) that compensates for high-frequency disturbances due to its lower inertia compared to other actuators. Additional actuators can be incorporated for specific purposes, such as fiber coupling or adjusting the point-ahead angle to compensate for signal propagation delays.

Multiple sensor sources are often employed to assist with alignment. Satellites are generally equipped with inertial measurement units, horizon and sun sensors, star trackers, and magnetometers. Moreover, an LCT typically includes a tracking sensor to detect the incoming beacon or data signal. This sensor may consist of two subsensors with differing field of view (FOV) and angular resolutions, enabling rapid signal acquisition followed by precise tracking. When multiple terminals are used on the same platform, the system must also support simultaneous tracking of multiple pointing targets.

2.2 Attitude Knowledge Transfer

Prior to each link, the LCT is commanded with the start and end times as well as the target information for that particular link. For ground stations as targets, e.g., the position of the target is expressed in the earth-centered, earth-fixed coordinate system (ECEF) frame. The LCT precomputes the position of the ground station in the international celestial reference frame (ICRF) frame at configurable time intervals. A default value of 1 s has proven to be sufficiently dense, with negligible impact on accuracy. Depending on the settings and link parameters, this procedure takes about 1 min, but it reduces the computational load during the link, since the target position at a given time can then be obtained by linear interpolation between the precomputed timestamped locations of the target.

To compute the updated position of the target, the current time must be known, which is the next step in the link procedure. The satellite sends a pulse per second (PPS) signal, and initially, the LCT is informed of the time at the next PPS pulse. This is subsequently used to synchronize the two clocks at that pulse. Thereafter, the LCT system uses the PPS signal to keep the clocks synchronized.

The LCT must then compute the required azimuth and elevation axis positions for a CPA to point the laser toward the ground station.

2.3 Attitude Propagation

Traditional CubeSat platforms consist of separate subsystems that operate independently, as described in Section 2.1. The proposed concept (Rüddenklau et al. (2025)) enhances performance by enabling information exchange between subsystems, particularly between the ADCS and the LCT, following the procedure outlined in Section 2.2. Since LCTs require faster control updates than typical ADCS systems, a dedicated propagation algorithm is introduced for the LCT (Garbagnati et al. (2025)). This algorithm is initialized with ADCS data and refined using onboard sensors such as micro-electro-mechanical system (MEMS) gyroscopes (see Fig. 1). The approach improves attitude knowledge between ADCS updates and can be extended to other high-rate sensors, provided that proper calibration is performed, as shown in Section 3.4.

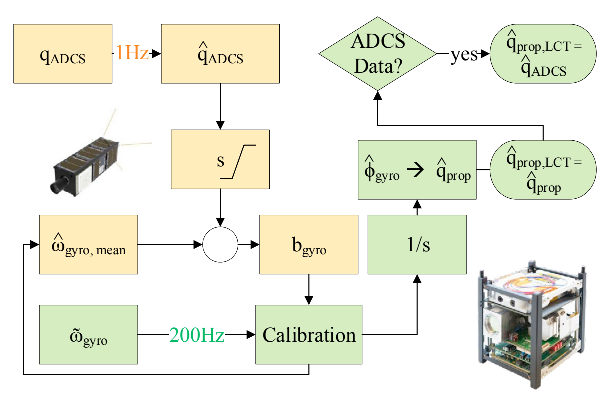

Fig. 1. Estimated attitude data from the ADCS (orange) is used and propagated within the LCT domain (green) using higher-rate gyroscope measurements to improve pointing knowledge of the terminal even in dynamic scenarios (Rüddenklau et al. (2025)).

As depicted, the satellite samples the precise estimated attitude and forwards it to the LCT at a nominal rate of 1 Hz. The LCT propagates this data at a higher sampling frequency using its less precise onboard sensors. This propagation accounts for dynamic attitude changes that would not be captured by linear extrapolation. The propagated attitude is compared with the pointing target vector, from which the pointing error is derived. Knowing this error allows the fine steering mirror (FSM) to compensate it in a feed-forward manner. Thus, the LCT compensates for the satellite's less accurate actuators by employing its FPA. Once the link is established, the FSM low-level controller re-references from the estimated attitude to the measured relative error provided by the quadrant photo diode (QPD), as described in Section 2.4.

2.4 Attitude Control

During the tracking phase, an optical reference beacon can be used to precisely determine the pointing reference to the communication partner. Classical systems either employ separate control loops for the ADCS and the LCT, or forward the optical reference to improve the pointing of the entire spacecraft (Paaras S. Agrawal and DiMatteo (2024)). Although this concept has been proven to work, it requires careful coordination, does not deal with multiple actuator systems, and often introduces additional work packages for the satellite manufacturer to understand the dynamics and limitations of the optical system. To address this, the concept of control allocation (Johansen and Fossen (2013)) is applied on the MAC to distribute control efforts among the subsystems. The approach not only enables the use of multiple actuators but also provides the additional benefit of optimizing for secondary objectives, such as minimizing power consumption, in overactuated systems. However, the general concept of control allocation must be adapted to the specific requirements of laser communication systems (Rüddenklau and Schitter (2025)).

Control allocation can be understood as the optimal high-level distribution of control, assuming that low-level controllers execute commands with defined precision and dynamics within their design limits. The control allocator accounts for these limitations, for instance, through least-squares optimization. For the ADCS, this means the attitude controller can operate independently of the acquisition or tracking phase, thereby avoiding control instabilities during mode transitions. Moreover, the MAC does not require deep insight into the satellite's control system, as long as its input-output behavior is known. The same principle applies to the LCT actuators, which are regulated by established low-level controller implementations. Consequently, the distribution of control efforts can also be performed at the actuator level, as illustrated in Figure 2.

This principle is especially advantageous in multi-link satellite configurations, as demonstrated by its use in constellations. Consequently, effort can be distributed among the satellite and all available terminals. In scenarios that require such advanced pointing capabilities, terminals are usually equipped with both a CPA and an FPA. This architecture results in an over-actuated system. Consequently, optimizations of secondary objectives, such as offloading the fine pointer, can be made while adhering to the principle of pointing precision.

From a project requirements perspective, whenever a subsystem is exchanged or fails during operation, the respective low-level controller must be tuned to fit the actuator

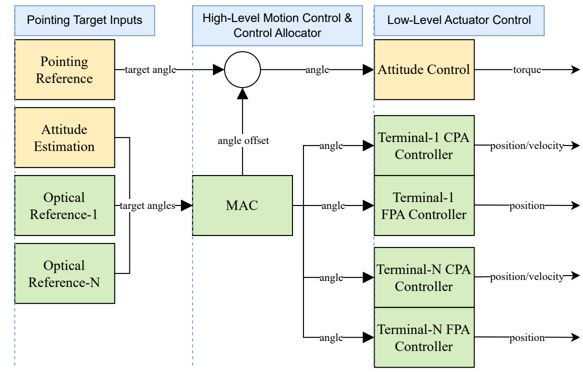

Fig. 2. The figure shows the control architecture with data from the ADCS (orange) and LCT data (green), where attitude estimation data is used by the MAC to augment attitude knowledge and its control output distributed among all subsystems.

or subsystem's new dynamics. However, control allocation provides a deterministic interface by updating control effectiveness parameters and limitations to account for the new actuator. Notably, this method is compatible with multiple control input sources, including ephemeris-based pointing data and simultaneous optical reference feedback. Control allocation enables the determination of the degree of trust allocated to each source, thereby preventing mode switching operations within the controller.

3. THE MASTER ATTITUDE CONTROLLER HARDWARE

The subsequent section addresses the project-level and hardware-level implications. This includes characterizing the onboard peripherals and detailing the considerations made for interfacing with surrounding subsystems.

3.1 Embedding in the OSIRIS Framework

The German Aerospace Center (DLR) has an established history of developing increasingly sophisticated control systems for optical communication payloads under the OSIRIS program. These early efforts laid the groundwork that led to the development of the MAC, shown in Figure 3.

The OSIRIS4CubeSat (O4C) (Schmidt et al. (2022)) mission, designed for direct to earth (DTE) optical links, utilizes an FPA consisting of an FSM and a QPD controlled by the optical terminals mainboard PCB. Its control algorithms run independent of the satellite bus. Coarse pointing for O4C relies entirely on the CubeSat's body pointing capabilities as the FPA itself is designed to operate independently of the satellite's ADCS.

The subsequent QUBE (Schmidt et al. (2022)) mission adopts O4C's FPA and control logic (Rüddenklau et al. (2024)), but introduces a more capable dedicated 16 bit microcontroller version upgrading from a 8 MHz to a 25 MHz processing clock. This redesign enhanced local processing capabilities, enabling communication with an onboard inertial measurement unit (IMU). It also enabled the implementation of the COMPASS (Dombrovski et al. (2018))

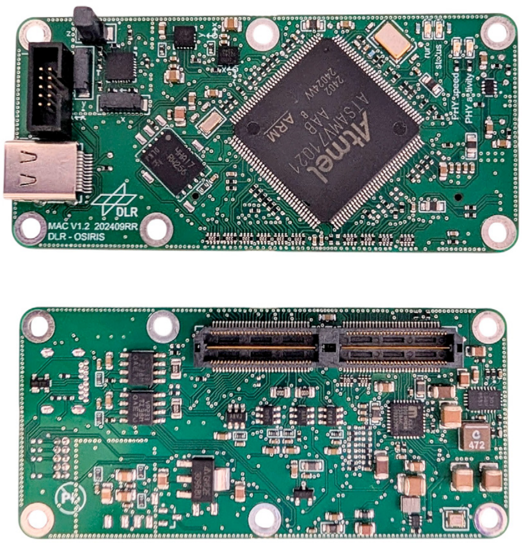

Fig. 3. MAC printed circuit board (PCB) presented from top and bottom view.

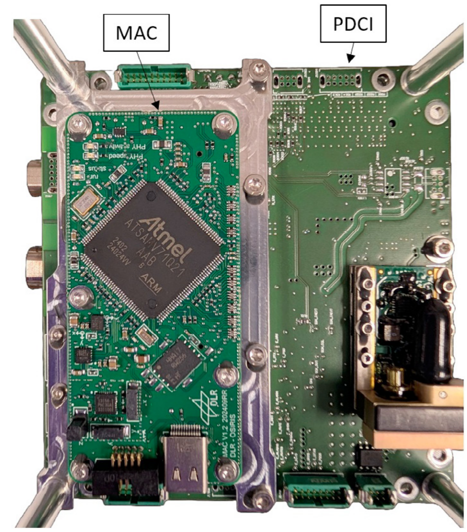

Fig. 4. Flight model of the PDCI and stacked MAC integrated in the CubeSat frame.

protocol, which is used, among other tasks, to periodically update and convert the FSM angle for transmission to the ADCS.

A significant turning point came with the CubeISL mission, driven by the stringent pointing requirements of an inter-satellite link (ISL). These demands necessitate an FPA sampling period increase to allow a faster scan pattern (Rüddenklau and Schitter (2024)). This is achieved by directly incorporating the satellite's ADCS data to the FSM control by feed-forward compensation of measured satellite drift (see Sec. 2.3).

The latest mission, Cube1G, aims to achieve complete LCT pointing independence from the satellite's attitude (Rödiger et al. (2025)). This involved combining the CubeISL optomechanics (Nonay et al. (2024)) with a CPA. This recurring pattern—escalating requirements driving hardware changes of the optical terminal's mainboard, extensive software porting, and increased processing power—highlighted the need for a more modular and sustainable architecture.

3.2 Interface Considerations

The following discussion concerns the latest generation of optical terminals, which consist of several subsystems that must communicate with each other. These include the ADCS, the data handling unit (DHU), an optical transmitter, an erbium doped fiber amplifier (EDFA), the optical terminal, a data receiver, a CPA, and the MAC. To design the interfaces efficiently, a so-called power distribution and control interface board (PDCI) was introduced (see Fig. 4). All subsystems are connected through this PCB, which provides both power and the required interfaces. The relevant internal interface for the MAC is discussed in the following. The PDCI is implemented as a single PCB in the PC/104 form factor (without the standard connector) and provides a stacking interface for the DHU on one side and the MAC on the other. It also includes all external physical interfaces to the satellite bus.

From a system perspective, the MAC functionality does not prescribe a specific hardware implementation. For the OSIRIS systems, the MAC was envisioned as a self-contained control unit that can be reused in multiple platforms without modification, necessitating a dedicated hardware component. However, to avoid being constrained to the PC/104 dimensions, a stacked PCB approach was adopted, in which the MAC is mounted on a carrier board. The module features a compact footprint of 75 mm by 35 mm. It is built around an ARM Cortex-M7 controller and incorporates a single high-density 60-pin connector, simplifying the interface while enabling multiple connections to other subsystems.

Supported communication buses include inter integrated circuit bus (I2C), serial peripherial interface (SPI), universal asynchronous receiver transmitter (UART), controller area network (CAN), and Ethernet. In addition, digital general purpose input output (GPIO) pins with interrupt functionality and analog interfaces are available. The MAC can operate over a wide supply voltage range from 4.5 V to 60 V, with at least 48 V defined as the minimum requirement for ongoing missions. This wide range is partly enabled by available commercial of the shelf (COTS) components and also removes the need for stringent supply requirements, thereby ensuring compatibility with a broad range of standard satellite power supplies. Typical power consumption is about 1 W during nominal operation.

3.3 Inter-Subsystem Communication

Separate UART interfaces are used for internal communication between the MAC, DHU and the optical payload's mainboard. This interface transfers three categories of data: low-frequency telemetry at 1 Hz, mid-frequency control data from 20 Hz to 200 Hz, and high-frequency scientific data from 1 kHz to 4 kHz for post-processing purposes. While the electrical interface to the satellite may vary depending on the mission, the software interface is designed to remain largely consistent and is either connected directly or routed via the DHU.

This design enables the satellite software to interact with the LCT through high-level commands, decoupling it from the details of how the MAC executes those commands. When a command is issued to prepare the system for a link, it specifies only the necessary link parameters rather than the individual tasks or states of each subsystem. The MAC software then determines how to configure and operate its subsystems to achieve the commanded link. Once all subsystems and the MAC itself are configured, the MAC returns confirmation to the satellite. This prevents internal changes from propagating to the satellite level, resulting in a more flexible and maintainable system.

3.4 Characterization of Onboard Peripherals

To enhance attitude knowledge during the acquisition phase and to characterize high-frequency micro-vibrations of the satellite, several COTS sensors are implemented on the MAC. Characterizing micro-vibrations is particularly relevant for the design of future terminals, although it is not strictly required to improve the performance of the current terminal. The objective is to obtain a comprehensive, data-backed spectrum of CubeSat micro-vibrations during pointing maneuvers and optical links. This is critical because sensitive components of optical terminals, such as the FSM, exhibit resonance frequencies that may overlap with the micro-vibration spectrum, introducing additional disturbances (Rüddenklau et al. (2025)).

The automotive-grade gyroscope (IAM20380, TDK InvenSense (2024)) provides selectable ranges from $250\,^\circ\,\mathrm{s}^{-1}$ to $2000\,^\circ\,\mathrm{s}^{-1}$ with a noise density of $0.008\,(^\circ/\mathrm{s})/\sqrt{\mathrm{Hz}}$ and output frequencies from 4 Hz to 1 kHz. Sampling at a frequency higher than the control loop mitigates lag as a potential error source. A calibration routine was developed using a standard least-squares method to correct for scale factor, non-orthogonality, and bias errors arising during manufacturing and integration. This algorithm can be executed either pre-flight on the ground or in orbit. Turn-on bias and random walk cannot be eliminated by static calibration, but are compensated by continuous in-flight offset calibration (see Sec. 2.3).

Figure 5 shows an excerpt of the 300 s calibration routine, during which the MAC was rotated about each axis with random target velocities and positions. Constant bias was successfully compensated, and errors were significantly reduced, particularly for the small-amplitude movements expected during the mission. As the hexapod provides only positional data, differentiation-induced errors may occur. For example, the maximum calculated reference velocity ($6.9\,^\circ\,\mathrm{s}^{-1}$) exceeded the maximum target velocity ($6.0\,^\circ\,\mathrm{s}^{-1}$), which explains the remaining discrepancy between measurement and reference during higher acceleration movements, that are not representative for a slewing satellite maneuver.

The industrial-grade accelerometer (IIM42352, TDK InvenSense (2022)) is suitable for high-frequency vibration measurements due to its output data rate of up to 32 kHz, low noise density of $70\,\mu\mathrm{g}/\sqrt{\mathrm{Hz}}$, and selectable measurement range from 2 g to 16 g. Calibration data, based on the measured response (Badri et al. (2011)), demonstrate a close agreement between the retrieved transfer function and that of a reference accelerometer (see Fig. 6).

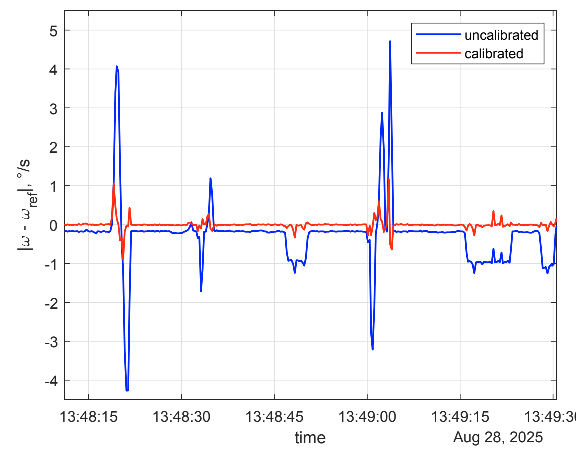

Fig. 5. Measurement error compared to reference values from hexapod (HXP50, Newport) for uncalibrated data (blue) and calibrated data (red).

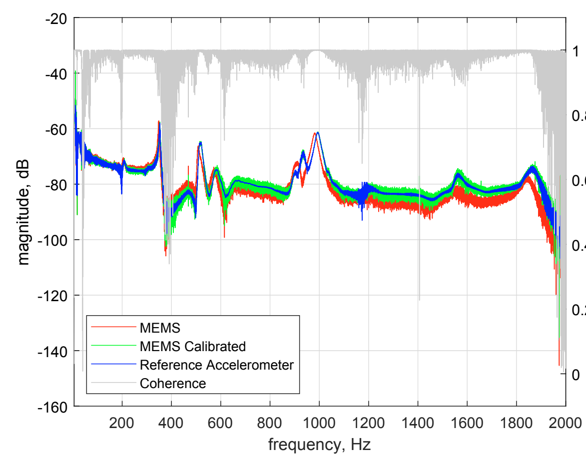

Fig. 6. Calibrated and uncalibrated transfer function spectrum in comparison with a calibrated reference accelerometer (355B04, PCB Piezotronics).

In addition to the sensors, the MAC incorporates a non space grade 1 Gbit flash memory (MT25QL, Micron Technology (2018)). This quad-SPI flash enables storage of high-frequency data. It also includes protected sectors for critical data, such as launch lock status and system boot count, which are stored with triple redundancy. Since the flash is not radiation-hardened, a radiation test was performed using a Cobalt-60 gamma irradiation source. The MAC was exposed to a total ionizing dose of 60 Gy at a rate of $50\,\mathrm{Gy\,h}^{-1}$, representative of a 5-year mission in a 500 km sun-synchronous orbit with 3.5 mm of aluminum shielding. No anomalies were observed following irradiation.

4. CONCLUSION AND SUMMARY

In this work, the MAC was introduced as a proposal for future laser communication systems on attitude-controlled platforms, which are often modular due to evolving mission requirements. It was shown how over-actuated systems can be leveraged to optimize secondary objectives and how thoughtful design of interfaces and additional sensors can unify implementation at the system level, enhancing overall performance. The generic nature of the MAC enables the use of existing LCTs and satellite buses in an as-is configuration, avoiding costly and error-prone redesigns of control loops and hardware.

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The TDK InvenSense sensors described in this publication were not designed, tested, or qualified for aerospace use. TDK InvenSense makes no representations or warranties regarding their suitability, reliability, or performance in such environments. Any use of these products in aerospace applications is entirely at the user's own risk. TDK InvenSense does not object to the research use of these products as described in this publication, but this does not constitute an endorsement or recommendation of these products in aerospace or space applications.

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