actuators

MDPI

Review

Latest Advances and Development Trends in Space Inertial Actuators

Huajun Zhou [1,2], Lei You [1], Xinsheng Wei [1,2,*], Hua Wei [2,*], Zeyuan Yu [2] and Zihao Fang [2]

[1] Shanghai Institute of Spacecraft Control Technology, Shanghai 201100, China; 230249801@seu.edu.cn (H.Z.); youlei12138@163.com (L.Y.)
[2] School of Electrical Engineering, Sipailou Campus, Southeast University, Nanjing 210096, China; 220253043@seu.edu.cn (Z.Y.); 15380928021@163.com (Z.F.)
* Correspondence: 13636398122@139.com (X.W.); huawei1978@seu.edu.cn (H.W.)

Abstract

Space inertial actuators, represented by reaction wheels, momentum wheels, flywheels, and control moment gyroscopes, are indispensable angular-momentum exchange devices in spacecraft attitude determination and control systems. Owing to their non-consumable operation, high reliability, and precise torque-generation capability, these actuators are widely employed for attitude stabilization, rapid attitude maneuvering, payload disturbance mitigation, and precision pointing in modern satellites and space vehicles. With the rapid growth of high-resolution Earth observation missions, deep-space exploration programs, and large-scale commercial satellite constellations, the performance requirements imposed on inertial actuators are becoming increasingly stringent. This paper systematically reviews the current state of the art in space inertial actuator technologies by integrating peer-reviewed research with publicly available industrial product information, and summarizes recent research progress, representative products, and development strategies in the United States, Europe, Russia, and China. By comparing the technical characteristics and evolutionary pathways of mainstream reaction wheel, momentum wheel, flywheel, and control moment gyroscope systems, the study identifies the principal technological drivers shaping future development. The analysis reveals five dominant trends: extended operational lifetime, higher control accuracy, greater torque and angular-momentum density, reduced micro-vibration disturbance, and scalable, cost-effective manufacturing. These findings provide a systematic technical reference for future research, engineering design, and industrial development of advanced space inertial actuator systems in China and internationally, particularly for next-generation spacecraft requiring long service life, high pointing accuracy, low disturbance, and scalable production.

Keywords: inertial actuator; flywheels; control moment gyroscopes (CMG); spacecraft attitude control; aerospace actuator technology

Check for updates

Academic Editor: Ronald M. Barrett

Received: 9 May 2026
Revised: 2 July 2026
Accepted: 3 July 2026
Published: 16 July 2026

1. Introduction

Space inertial actuators, principally reaction wheels (RWs) and control moment gyroscopes (CMGs), constitute core single-unit devices for non-consumable angular-momentum exchange in spacecraft attitude-control systems [1,2]. By avoiding propellant depletion and plume contamination, they are extensively applied in attitude stabilization, rapid maneuvering, precision pointing, and scanning payload isolation [3]. Mechanically, RWs generate control torque about a fixed axis by modulating rotor velocity, whereas CMGs reorient a nearly constant angular-momentum vector through motorized gimbals, thereby amplifying output torque through gyroscopic precession [4]. In the contemporary era of high-resolution Earth observation, deep-space exploration, and agile on-orbit operations, optimizing these electromechanical devices is of considerable strategic importance for modern high-agility space missions [1–5].

Driven by the requirements of both flagship exploration missions and commercial New Space constellations, including China's GW and Qianfan mega constellations and international programs such as Starlink, contemporary R&D is increasingly directed toward hybrid magnetic bearings (HMBs) to reduce tribological wear, as well as radiation-tolerant COTS DSP/ARM architectures capable of implementing advanced control strategies, such as active disturbance rejection control (ADRC), linear extended state observers (LESOs), and active vibration control (AVC) loops. However, substantial engineering barriers persist, including the elevated control complexity and power demand associated with gyroscopic-precession-based torque generation, touchdown risks caused by narrow 0.2–0.5 mm magnetic-bearing air gaps, software and computational overheads introduced by runtime single-event-upset (SEU) mitigation, and scalability challenges for high-rate automated assembly.

To strengthen the scholarly foundation of this review, the present study integrates industrial product data with representative peer-reviewed research on space inertial actuators. Rather than treating actuator performance as a set of isolated commercial specifications, this review interprets product-level indicators in relation to the scientific and engineering issues that govern actuator design, qualification, and spacecraft integration. The literature is organized around reaction wheel modeling and torque control, control moment gyroscope dynamics and steering laws, magnetic-bearing flywheel technology, bearing and lubrication lifetime, micro-vibration generation and transmission, passive and active vibration isolation, disturbance rejection, high-speed motor-drive design, fault diagnosis and fault-tolerant control, radiation-tolerant embedded electronics, reliability assessment, and spacecraft-level integrated attitude control. This organization establishes a systematic connection between actuator parameters and the modeling assumptions, control architectures, failure mechanisms, qualification constraints, and mission-level trade-offs reported in academic studies. By combining product benchmarking with critical literature synthesis, this review aims to clarify current technological limitations and identify future research directions for long-life, high-precision, high-torque-density, low-disturbance, and highly reliable space inertial actuators.

To address these challenges, this review presents a comprehensive international benchmarking and trend analysis of space inertial actuator technologies. Section 2 systematically surveys global product lines from leading manufacturers in the United States, Europe, Russia, and China, documenting key performance specifications, including angular momentum capacity, torque output, mass, power consumption, and operational lifetime. Section 3 analyzes physical scaling laws and hardware bottlenecks through quantitative performance distribution analysis, identifying five major development trends: extended service life, improved control precision, increased torque capacity, reduced micro-vibration disturbance, and lower manufacturing cost. These trends are substantiated through comparative evaluation of bearing lubrication strategies, magnetic suspension technology, sensor architectures, advanced control algorithms, passive/active damping mechanisms, and design-for-manufacturing (DFM) principles. Section 4 synthesizes strategic innovations and industrial implications, emphasizing the transition from customized, low-volume production toward scalable manufacturing frameworks, and identifies critical research frontiers required to bridge the performance-cost gap in the era of mega-constellation deployment.

2. Methodology Framework

To enhance the methodological rigor of this review, the literature and industrial evidence were organized through a structured narrative-review and engineering-benchmark framework. The review focuses on space inertial actuators used in spacecraft attitude determination and control systems, including reaction wheels, momentum wheels, flywheels, magnetically suspended flywheels, and control moment gyroscopes. Because detailed flight qualification records, bearing-life tests, and disturbance spectra are not uniformly available in the public domain, this study does not claim to constitute a quantitative meta-analysis. Instead, it follows an explicitly defined search, screening, classification, and synthesis procedure to connect accessible academic literature and traceable product data with the mechanisms that determine actuator performance.

2.1. Literature Search Scope and Data Sources

The literature search covered publications and technical materials from 2000 to 2026, with particular emphasis on studies published during 2019–2026, because recent commercial constellations, high-resolution optical payloads, agile spacecraft platforms, and long-life missions have substantially increased the requirements for torque density, low disturbance, reliable embedded computation, radiation tolerance, and fault-tolerant operation. Academic sources were searched through Web of Science, Scopus, IEEE Xplore, ScienceDirect, SpringerLink, AIAA publications, and Google Scholar. Source categories included peer-reviewed journal articles, high-quality conference papers, mission-related technical reports, manufacturer datasheets, product manuals, institutional reports, and traceable public materials [6].

The search logic combined actuator-type terms with mechanism- and application-level terms. Actuator-type terms included: reaction wheel, momentum wheel, flywheel, magnetically suspended flywheel, magnetic bearing reaction wheel, control moment gyroscope, single-gimbal CMG, and spacecraft inertial actuator. These terms were combined with: spacecraft attitude control, torque ripple, bearing friction, lubrication lifetime, rotor dynamics, high-speed motor drive, radiation-tolerant electronics, fault diagnosis, fault-tolerant control, steering law, singularity avoidance, micro-vibration, active vibration control, disturbance isolation, feedforward cancellation, payload pointing stability, and integrated attitude and vibration control. Industrial data were collected only when the source was traceable to publicly available datasheets, product brochures, institutional reports, conference materials, or official technical documents [7].

2.2. Screening Criteria and Synthesis Strategy

The collected material was screened according to relevance, technical specificity, and traceability. Titles, abstracts, keywords, and source descriptions were first examined to remove studies unrelated to spacecraft inertial actuators or attitude control. The remaining material was retained only when addressing the modeling, design, control, testing, reliability, vibration behavior, fault diagnosis, fault-tolerant operation, or spacecraft-level application of reaction wheels, momentum wheels, flywheels, magnetically suspended systems, or control moment gyroscopes. Excluded material comprised studies on terrestrial flywheel energy storage, general non-space motor drives, non-space industrial actuators, duplicated product descriptions, non-traceable commercial claims, and promotional statements without technical content [8].

The retained material was classified into five thematic dimensions corresponding to the principal development trends analyzed in this review: (i) long service life and reliability (bearing tribology, lubrication management, magnetic suspension, radiation hardening, and life-test qualification); (ii) high-precision control (sensors, motor-drive architectures, embedded control hardware, and advanced control algorithms); (iii) high torque and angular-momentum density (electromagnetic topology, high-speed rotor structures, thermal management, and CMG gimbal dynamics); (iv) low disturbance vibration (micro-vibration generation and transmission, passive/active isolation, and magnetic-bearing-based active vibration control); (v) cost-effective manufacturing and commercialization (COTS component adoption, system-level redundancy, design-for-manufacturing, automated production, and constellation-oriented actuator scaling).

Cross-cutting topics such as spacecraft-level integrated attitude control and fault-tolerant operation were assigned to the dimension most closely aligned with their primary contribution, while their system-level implications were synthesized across multiple dimensions where necessary.

The synthesis was conducted in three steps: first, representative product data were used to identify observable development patterns; second, academic studies were used to interpret the mechanisms behind those patterns; and third, the results were organized around the same five development trends long service life, high-precision control, high torque output, low disturbance vibration, and commercialization so that the evidence flow from component-level design choices to system-level performance is kept transparent and traceable.

2.3. Methodological Limitations

Several limitations must be acknowledged. First, qualification procedures, bearing-life test results, in-orbit anomaly records, radiation test details, and disturbance spectra are largely proprietary and are not available with consistent depth across manufacturers. Second, actuator specifications depend on mission class, orbit, payload sensitivity, thermal-vacuum environment, radiation design philosophy, redundancy architecture, and spacecraft structural coupling; therefore, nominal performance figures cannot be compared without considering test context and mission assumptions. Third, commercial space products evolve rapidly, making some product information time-sensitive. The conclusions of this review should therefore be interpreted as a structured synthesis of accessible academic and industrial evidence aimed at identifying technical mechanisms and research gaps, rather than as a certification ranking of individual actuator products.

3. Current Development Status Domestically and Abroad

As core components of high-precision satellite attitude control systems, space inertial actuators have seen rapidly increasing demand alongside the rapid expansion of satellite constellations. The global market for reaction wheels and control moment gyroscopes has expanded markedly, driven by both traditional government-led space programs and the emerging commercial New Space sector. Leading international research institutions and manufacturers include Honeywell in North America, Collins Aerospace, Airbus, and Comat in Europe, and the Central Research Institute of Command Devices in Russia. In China, representative institutions and enterprises include the Beijing Institute of Control Engineering, Shanghai Aerospace Control Technology Research Institute, Hunan Lanyue Electromechanical Technology Co., Ltd., Changsha, Hunan Province, China and Beijing Yidong Aerospace Technology Co., Ltd., Beijing, China. This section systematically benchmarks the technical specifications, flight heritage, and market positioning of these key global players to establish a comparative basis for subsequent trend analysis.

3.1. United States

With Honeywell as the representative manufacturer, the United States maintains a globally leading position in the research, development, and manufacturing of space inertial

https://doi.org/10.3390/act15070399

actuator technologies. Honeywell's products set industrial benchmarks for precision, performance, and reliability, underpinned by decades of flight heritage across NASA missions, U.S. Department of Defense satellites, and international commercial platforms. The company's actuators are widely deployed in critical applications, including satellite attitude control, stabilization, and precision pointing for Earth observation and deep-space exploration missions [9,10].

Honeywell's reaction wheel product line spans angular momentum capacities from 1 to 100 N·m·s, offers speed control accuracy of 0.1 rpm, and provides design lifetimes up to 15 years under continuous operation in geostationary and low-Earth-orbit environments. The product portfolio is designed with modular scalability, enabling mission designers to select configurations optimized for satellite mass classes ranging from small LEO platforms (~100 kg) to large geostationary communication satellites (>3000 kg). Table 1 summarizes Honeywell's comprehensive flywheel product portfolio [11].

Table 1. Honeywell's Flywheel Product Lineup in the United States.

Product Line	HR04	HR12–25	HR12–50	HR14–75	HR16–100
Mass (kg)	<2.6	7	9.5	10.6	12
Maximum power consumption (W)	48	195	195	195	195
Maximum speed (rpm)	9000	6000	6000	6000	6000
Angular momentum (N·m·s)	1	25	50	75	100
Torque (N·m)	0.030	0.4	0.4	0.4	0.4
Service life (years)	10	15	15	15	15

The HR04 is a high-performance reaction wheel specifically designed for commercial aerospace applications, particularly for the rapidly growing small-satellite and constellation markets. This compact unit supports multiple digital interface options, including RS422, CAN, and LVDS protocols, facilitating seamless integration with diverse satellite bus architectures. The HR04 delivers high-precision, low-disturbance torque output with jitter levels below 10^{-4} N·m, making it suitable for high-resolution imaging payloads and precision-pointing applications. Consequently, the HR04 has achieved extensive deployment in the commercial aerospace market, with over 500 units successfully operating in orbit as of 2024. The unit's robust thermal design enables operation across a wide temperature range, while its radiation-hardened electronics ensure reliable performance in moderate radiation environments with total ionizing dose tolerance up to 50 krad.

3.2. Europe

3.2.1. Collins Aerospace (Germany)

Collins Aerospace Germany is recognized for reaction wheel products characterized by high precision and high reliability. These actuators are widely used in European Space Agency (ESA) satellite platforms and have achieved significant international adoption [12]. The company maintains well-established capabilities in aerospace technology research, development, and manufacturing, with reaction wheel products spanning an angular momentum range of 0.04–100 N·m·s. Collins Aerospace's products address mission requirements ranging from CubeSats to large geostationary platforms [13,14]. As shown in Table 2.

The RSI product line employs advanced bearing lubrication systems based on vacuum-stable synthetic oils, supporting long-duration operation with a qualified service life of up to 15 years. The flagship MWI 100-100/100 momentum wheel incorporates redundant sensor arrays and dual-channel drive electronics to support fault-tolerant operation and improve mission reliability.

Table 2. Product Lineup of Collins Aerospace's Flywheel Products.

Product Line	RSI 01-5/15	RSI 02-33/30	RSI 4-75/60	RSI 12-75/60	RSI 25-75/60	RSI 68-75/60	MWI 100-100/100
Mass (kg)	0.6	1.75	3.7	4.85	6.3	8.5	16.8
Maximum power consumption (W)	4	20	90	90	90	90	300
Maximum speed (rpm)	1500	3000	6000	6000	6000	6000	10,000
Angular momentum (N·m·s)	0.04	0.2	4	12	25	68	100
Torque (N·m)	0.005	0.033	0.075	0.075	0.075	0.075	0.1
Service life (years)	15	15	15	15	15	15	20

3.2.2. Airbus

Established in 1970 as a multinational European consortium for civil aircraft manufacturing, Airbus subsequently expanded into the defense, space, and helicopter sectors. Following the 2014 consolidation of its space activities with Astrium, Airbus organized its satellite and launcher operations under Airbus Defence and Space [15]. The company has developed a comprehensive portfolio of control moment gyroscopes for high-agility satellite platforms. Table 3 summarizes the company's CMG product lineup [16].

Table 3. Airbus's Control Moment Gyroscope Product Lineup Table.

Product Line	CMG15-45S	CMG40-60S	CMG4-6S
Mass (kg)	18.4	38	13
Power consumption (W)	25	49	20
Angular momentum (N·m·s)	15	30–40	4
Torque (N·m)	45	60	6
Service life (years)	10	10	8

The CMG40-60S is a compact, high-performance control moment gyroscope equipped with an integrated micro-vibration damper and optimized for satellites in the 1000–2000 kg class. The unit employs an optimized assembly architecture to reduce volume and mass while preserving the required performance specifications. The integrated micro-vibration damper reduces transmitted forces to the spacecraft bus by 15–20 dB in the 50–500 Hz frequency band [17,18]. The CMG40-60S has been successfully deployed on multiple European Earth observation satellites, demonstrating reliable performance under demanding operational conditions. As shown in Figure 1.

3.2.3. Comat

Founded in 1977, Comat contributed to early FOTON missions aboard the Mir space station and subsequently participated in International Space Station (ISS) development, establishing close collaboration with ESA. This experience has provided the company with substantial flight heritage in harsh space environments over several decades. The company's reaction wheels are mainly deployed in small commercial satellite platforms, from CubeSats to minisatellites [19]. As shown in Table 4.

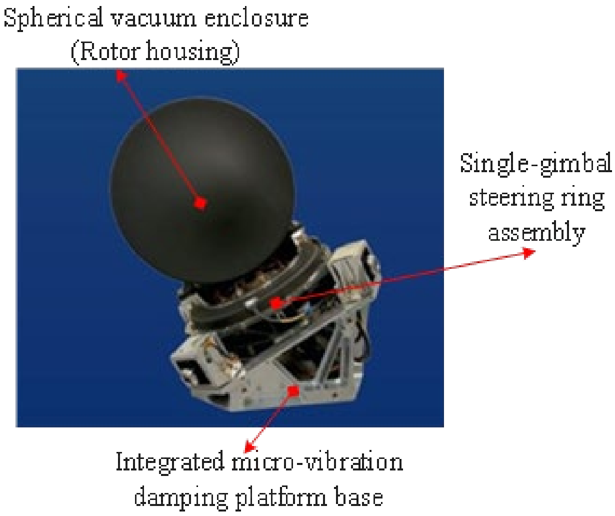


Figure 1. CMG40-60S (Image courtesy of Airbus; used with permission).

Table 4. Product Lineup of Comat's Flywheel Products.

Product Line	RW40	RW40	RW60	RW180-500	RW1-2k
Mass (kg)	0.142	0.23	0.27	0.66 (0.18 N·m) 0.91 (0.5 N·m)	1.4 (1 N·m) 1.7 (2 N·m·s)
Maximum Power consumption (W)	3.5	6.2	7.7	65	65
Maximum speed (rpm)	6000	6000	6000	6000	6000
Angular momentum (N·m·s)	0.02	0.04	0.06	0.18–0.5	1–2
Torque (N·m)	0.002	0.004	0.006	0.1	0.1
Service life (years)	8	8	8	10	10

To enhance image stability during Earth observation missions, Comat has developed dedicated vibration dampers for the RW40 and RW60 product lines. This integrated damping system effectively attenuates micro-vibrations induced by reaction wheel operation, reducing transmitted disturbance forces by 10–15 dB across the 20–200 Hz frequency band. By limiting disturbance transmission, the system mitigates degradation of telescope pointing accuracy and improves overall imaging performance. The damped reaction wheel series has been successfully deployed on multiple commercial Earth observation satellites, demonstrating measurable improvements in image quality. As shown in Figure 2.

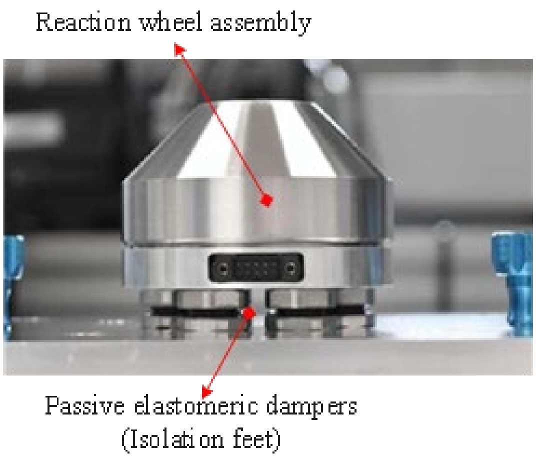


Figure 2. RW40 with Dampers Installed (Image courtesy of Comat; used with permission).

3.3. Russia

The Central Research Institute of Command Devices in St. Petersburg serves as the principal developer of space inertial actuators in Russia. The institute has maintained continuous development and production of control moment gyroscopes for over five decades. Its CMG product line covers angular momentum capacities from 100 to 5000 N·m·s, addressing requirements from medium-sized satellites to large space stations. To date, the institute has manufactured more than 500 single-gimbal CMG units, which have been extensively deployed across various Russian spacecraft platforms [20,21]. As shown in Table 5.

Table 5. Control Moment Gyroscope Products of the St. Petersburg Instrument-Marking Institute.

Product Line	KyPbEP-C	KEHATBP-M	KPyИ3
Mass (kg)	40	248	75
Power consumption (W)	30	165–290	80
Angular momentum (N·m·s)	100	2500, 2000 1500, 5000	250
Torque (N·m)	±12	±873	±44
Service life (years)	1	2	3

The KEHATABP-M series represents the institute's large-capacity CMG platform, specifically designed for massive space stations and heavy geostationary satellites. This product line offers configurable angular momentum options to accommodate diverse mission profiles. The maximum output torque of ±873 N·m supports rapid attitude slewing for multi-ton spacecraft, which is critical for attitude acquisition and disturbance rejection [22]. As shown in Figure 3.

Figure 3. Product Drawings and Specifications of the St. Petersburg Instrument-Making Institute.

3.4. China

3.4.1. Hunan Lanyue Electromechanical Technology Co., Ltd.

Established in 2017, Hunan Lanyue Electromechanical Technology Co., Ltd. was formed around a core technical team from the National University of Defense Technology. As shown in Table 6. Leveraging this technical foundation, the company has progressively launched reaction wheel products covering angular momentum capacities from the millinewton-meter-second class to 15 N·m·s. These products serve domestic commercial aerospace enterprises and have been successfully deployed in multiple in-orbit satellite platforms. The company has established automated production lines capable of delivering hundreds of units annually to support constellation-scale deployment schedules [23]. As shown in Figure 4.

Table 6. Product Lineup of Hunan Lanyue Electromechanical Technology Co., Ltd. Reaction Wheels.

Product Line	3 mNms	80 mNms–B	0.6 Nms–A	6 Nms–A	8 Nms–A	12 Nms–B	15 Nms–B
Mass (kg)	0.090	0.48	1.0	4.3	5.0	10.5	7.2
Maximum power consumption (W)	2.5	6	35	160	165	180	175
Maximum speed (rpm)	6000	7200	6000	5500	5500	1300	5000
Angular momentum (N·m·s)	0.003	0.08	0.6	6	8	12	15
Torque (N·m)	0.00045	0.005	0.02	0.2	0.2	1	0.2
Service life (years)	7	7	7	7	7	7	7

(**a**) (**b**)

Figure 4. Hunan Lanyue Flywheel Products. (**a**) Square structural flywheel; (**b**) Cylindrical structural flywheel.

3.4.2. Beijing Institute of Control Engineering

The Beijing Institute of Control Engineering has developed a comprehensive product line of momentum wheels and control moment gyroscopes, accumulating extensive flight heritage. The institute has established a complete series spanning large, medium, small, and micro-scale CMG configurations, with multiple models currently operational in orbit. The approximately 1:1 torque-to-angular-momentum relationship reflects optimized gimbal motor design for rapid-response applications.

In response to expanding commercial space demand, the institute is accelerating new flywheel product development and has initiated mass production operations at its dedicated manufacturing base. The facility currently maintains production capacity exceeding 3000 actuator units annually. This capacity expansion directly supports China's mega-constellation deployment programs, which are expected to require thousands of actuator units over the next decade. As shown in Figure 5. (The equipment shown in the figure is a 5 N·m/s variable-speed control moment gyroscope with nameplates.)

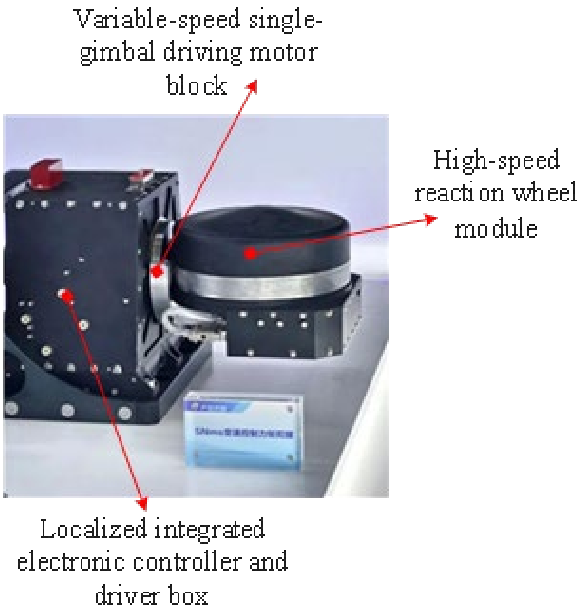


Figure 5. Beijing Institute of Control Engineering's Torque Gyro Products.

3.4.3. Shanghai Aerospace Control Technology Research Institute

The Shanghai Aerospace Control Technology Research Institute's reaction wheel product portfolio covers angular momentum capacities from 0.2 to 125 N·m·s, achieving speed control accuracy of 0.1 rpm and design lifespans of 8 years. The institute's CMG product line covers angular momentum ranges from 1 to 1000 N·m·s, with low-speed gimbal control accuracy of 0.005°/s and operational lifespans exceeding 8 years. These specifications support the requirements of a broad range of Chinese government and commercial satellite programs.

The institute has actively responded to commercial space development opportunities, resulting in widespread in-orbit deployment of its actuator products across multiple satellite platforms. Its products have been integrated into various Chinese satellite constellations, demonstrating reliable operational performance. As shown in Figure 6.

Figure 6. Shanghai Aerospace Control Technology Research Institute Flywheel Products.

3.5. Technical Analysis of Current Products

The product-level comparisons presented in Sections 3.1–3.4 reveal several common technical characteristics that underlie the observed performance differences. These characteristics reflect fundamental design choices and engineering tradeoffs in rotor architecture, bearing support, motor-drive topology, thermal management, sensing strategy, embedded electronics, and qualification philosophy. The following subsections summarize the key technical features that are consistently observed across the international product lines surveyed.

(i) Torque Density: Electromagnetic and Structural Determinants

The torque output per unit mass of a reaction wheel is primarily governed by its electromagnetic design and by how effectively the rotor inertia is distributed relative to total system mass [24,25]. High torque density requires both a motor with excellent current-to-torque conversion efficiency and a rotor that maximizes angular momentum storage without excessive weight [26]. In practice, this is achieved through optimized motor winding configurations and the use of lightweight composite rotor rims that allow higher rotational speeds without exceeding material stress limits. Among existing products, international manufacturers tend to exhibit higher torque density, largely because of refined motor slot-fill techniques and more mature composite consolidation processes [27]. Domestic commercial products still show a noticeable gap in this respect, which points to motor manufacturing precision and rotor structural integration as the main areas where capability-building is ongoing. For control moment gyroscopes, torque density further depends on gimbal motor performance, gimbal structural stiffness, and the amplitude of stored angular momentum factors that are closely coupled through the overall gimbal-frame design.

(ii) Bearing and Lubrication Technology: Lifetime Determinants

The operational lifetime of a ball-bearing reaction wheel is fundamentally constrained by the behavior of the lubrication system under space conditions. In the high-vacuum environment, lubricant evaporation and film breakdown represent the dominant failure modes, rather than classical rolling-contact fatigue alone. Current designs universally rely on specially formulated space-grade lubricants—typically multiply alkylated cyclopentane oils or perfluoropolyether greases—and many include passive or active oil-supply mechanisms to replenish the lubricant film over time. The ability to maintain an adequate film thickness throughout the mission directly dictates whether a unit can achieve long, trouble-free operation. Products with longer qualified lifetimes generally benefit from more comprehensive lubrication management strategies and from extensive accelerated life-test programs that validate the tribological design. It is widely acknowledged that the lifetime gap observed between some domestic products and their Western equivalents originates predominantly from this tribological qualification domain, rather than from fundamental differences in bearing materials or geometry. Design practice keeps contact stresses conservative to avoid subsurface plastic deformation, thereby providing a solid mechanical foundation on which the lubrication system can perform reliably.

(iii) Magnetic Suspension: Disturbance Spectrum Transformation

The introduction of magnetic suspension—whether through fully active magnetic bearings or hybrid configurations—fundamentally alters the micro-vibration signature of an inertial actuator. In conventional mechanical bearings, the disturbance force spectrum contains deterministic harmonic content linked to rotor imbalance, ball-pass frequencies, and cage instability, in addition to a broadband random component. Magnetic levitation removes the physical contact that generates many of these disturbances, leading to a substantial reduction of high-frequency vibration measured at the actuator interface. Residual disturbances, primarily from residual rotor imbalance and motor cogging, can be further suppressed by active vibration control algorithms integrated into the levitation control loops. However, magnetic suspension can introduce low-frequency force components within the bandwidth of the levitation controller, which must be carefully evaluated against the specific sensitivity profiles of the payload. This trade-off means that, while magnetic suspension offers an effective pathway toward ultra-low-disturbance actuation, its net benefit depends on matching the control architecture to the mission's stability requirements and on ensuring adequate shock resistance during launch.

(iv) Embedded Control Hardware: Algorithmic Constraints

The processing platform integrated into the actuator electronics largely determines the complexity and bandwidth of the control algorithms that can be deployed in orbit. Space-qualified processing solutions span a spectrum from simple radiation-hardened logic devices to more capable microprocessors. At the simpler end, antifuse-based field-programmable gate arrays offer deterministic, low-latency control at relatively low sampling rates; this makes them suitable for classical proportional-integral speed loops but limits the implementation of advanced observer-based or adaptive schemes. At the higher end, radiation-tolerant digital signal processors and microcontrollers with hardware floating-point support enable higher sampling rates and more computationally intensive algorithms, which can improve disturbance rejection and fault-tolerant capability. However, incorporating fault-tolerance mechanisms such as triple modular redundancy and error-correction coding consumes a significant fraction of the available processing cycles, effectively capping the algorithmic complexity that can be accommodated in real time. Consequently, current products reflect a pragmatic balance: the control architecture is co-designed with the chosen electronics platform so that performance, reliability, and cost constraints are satisfied simultaneously within a qualified radiation environment.

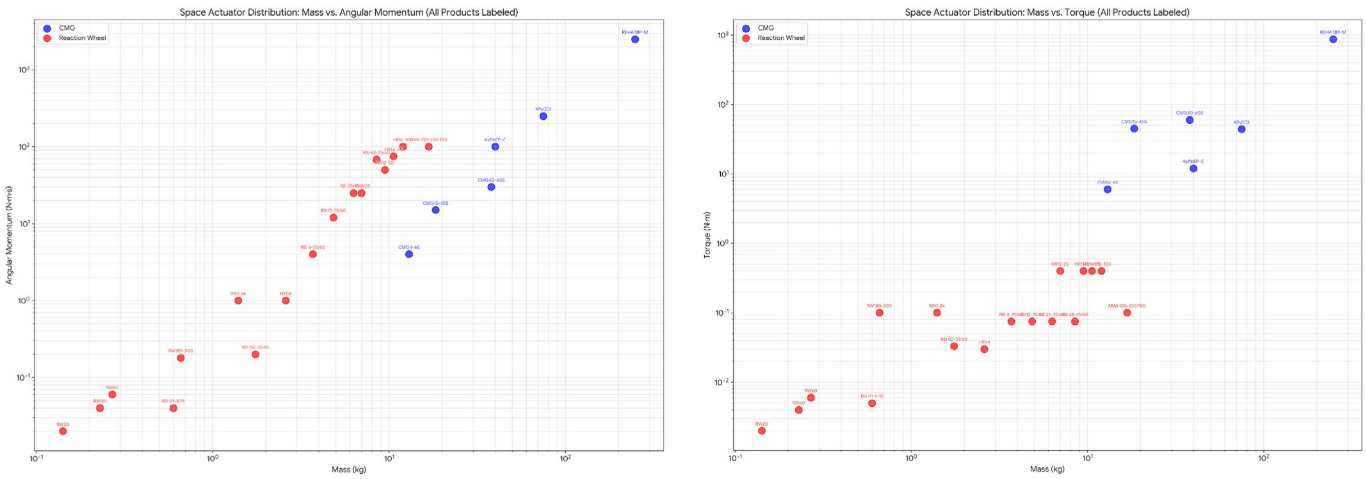
Collectively, these characteristics—torque density limited by electromagnetic and structural integration, service life dominated by tribological qualification, vibration behavior transformed by magnetic suspension, and control performance shaped by embedded electronics constraints—define the technical baseline upon which future developments are being built. They also clarify why simple comparison of datasheet numbers can be misleading unless the underlying engineering trade-offs are understood.

4. Trends in Space Actuator Development

Space inertial actuators are critical components for spacecraft attitude control and precision maneuvering. With the rapid expansion of satellite constellations and the increasing complexity of mission profiles, future development must prioritize extended operational lifetime, enhanced control precision, high torque-output capacity, and ultra-low disturbance characteristics.

To ensure consistent and objective evaluation across highly diverse mission paradigms—ranging from ultra-reliable deep-space exploration to cost-optimized commercial constellations—this review establishes a normalized baseline grounded in hardware scaling laws. Products are evaluated primarily by torque density (output torque per unit mass) and angular momentum capacity relative to system mass, metrics that isolate structural and electromagnetic efficiency from mission-specific platform constraints. Operational lifetime and radiation tolerance are categorized under two distinct design philosophies: traditional high-reliability standards (typically $\geq$15 years, employing antifuse FPGA or radiation-hardened architectures) and commercial New Space frameworks ($\leq$10 years, utilizing COTS-based system-level redundancy). All tabulated performance metrics throughout Section 2 reflect maximum qualified ratings under standardized vacuum-thermal conditions, ensuring baseline parity across heterogeneous international manufacturers.

Guided by these evaluation criteria, Figure 7 quantitatively illustrates the performance distribution of mainstream space inertial actuators worldwide. The analysis reveals two parallel development trends: first, a pronounced clustering of products with masses below 1 kg and angular momentum capacities of 0.01 to 1 N·m·s, directly reflecting the commercial aerospace sector's urgent demand for microsatellite platforms; and second, in high-performance domains, steadily improving torque-output efficiency per unit mass under comparable output-torque conditions. This trajectory indicates that future research will concentrate on breakthroughs in extended-life reliability, high-precision control, elevated torque density, and ultra-low vibration disturbance.



(**a**) Angular Momentum vs. Mass Distribution

(**b**) Output Torque vs. Mass Distribution

Figure 7. Comparative Chart of International Inertial Actuator Product Performance.

4.1. Long Service Life

Orbital satellite missions typically require operational lifetimes exceeding 10–15 years under extreme environmental conditions, including severe temperature cycling, high-energy radiation, and hard vacuum. To satisfy long-duration mission requirements such as deep-space exploration, constellation networking, and Earth observation, trouble-free operation beyond 15 years is essential.

Achieving extended service life in space inertial actuators, therefore, requires addressing the lifetime limitations of bearings, electronic components, and other critical subsystems.

4.1.1. Bearing Degradation Mechanisms and Active Life Extension

The long-life index of an inertial actuator depends first and foremost on the degradation rate of the bearing/suspension subsystem. For mechanically bearing flywheels, which still account for the majority of in-orbit operations, Hertzian contact fatigue and the gradual dissipation of lubricant are the two fundamental physical processes that determine the effective service life. Ye et al. [28] performed a transient dynamic finite element simulation of a B7007C/P4 angular contact ball bearing under an axial preload of 80 N and a rotational speed of 9000 r/min. They showed that the maximum contact stress at the ball–inner-ring raceway interface can reach 1019.6 MPa, deviating by only 5.2% from the classical Hertzian solution. Such cyclic stress inevitably leads to subsurface fatigue spalling over long-term operation; consequently, even when high-cleanliness bearing steel is used, the rated life of a mechanical flywheel bearing usually cannot exceed the 8- to 10-year design limit.

To compensate for the evaporation and migration loss of lubricant in a vacuum environment, Li et al. [29] proposed an active lubrication system based on a ring-shaped piezoelectric micro-injection device that can be fully embedded in the shaft system. Driven by a PZT-5H piezoelectric vibrator, the device generates local acoustic pressure pulses under rectangular-wave excitation and delivers fresh lubricant to the raceway with an accuracy of 0.012 μL per pulse. Experiments on a 6004 deep-groove ball bearing in a completely starved state showed that only 20 excitation pulses (a total delivered volume of about 0.55 μL) were sufficient to rebuild an effective elastohydrodynamic lubrication (EHL) film at 2250 r/min, restoring the friction torque to its normal level. When the oil supply was further increased, the friction torque actually rose because of viscous drag. This "U-shaped" torque-versus-oilquantity relationship confirms the necessity of on-demand active lubrication for extending bearing life. Meanwhile, Hu et al. [30] and He et al. [31] respectively constructed bearing degradation trend prediction methods based on an ECA-BiLSTM state-space model and an improved GMDH network. On the PHM2012 accelerated-life data set, the root-mean-square prediction errors of the two methods were as low as ~0.022 and ~0.005, enabling early identification of the performance degradation turning point. Therefore, combining such data-driven models with active micro-lubrication devices holds the promise of transforming the traditional "open-loop periodic oil replenishment" product philosophy into a closed-loop health-management paradigm of "on-orbit condition-based maintenance," thereby fundamentally breaking the long-life bottleneck of mechanical flywheels.

4.1.2. Degradation Factors in Magnetically Suspended Actuators and Control-Based Life Extension

For magnetically suspended reaction wheels or control moment gyroscopes, the main contradiction for long life shifts from mechanical wear to the gradual degradation of the electromagnetic-electronic system. Cheng et al. [32] established a composite degradation model of a magnetically suspended flywheel that accounts for the thermal demagnetization of permanent magnets and the gain attenuation of the power amplifier. They used an improved CNN-LSTM calibration network to track the multi-source degradation trajectories over the entire life cycle, achieving a normalized root-mean-square prediction error of only 7.22×10^{-4}—significantly better than a single LSTM or conventional CNN-LSTM. This provides an algorithmic foundation for the on-orbit digital twin and predictive health management of magnetically suspended actuators. At the hardware level, the four-degree-of-freedom hybrid active magnetic bearing designed by Krishnan et al. [33] supplies bias flux with permanent magnets, keeping the steady-state levitation power consumption below 1 W; consequently, the temperature rise and thermal-cycling stress of the power devices are greatly reduced. Ratheesh et al. [34] further tapped the potential at the control level: the pseudo-derivative feedback (PDF-II) controller they proposed, together with a zero-power integrator, slashed the levitation bias current from the conventional 1.4 A to below 200 mA, reducing the per-channel power amplifier dissipation by about 80%. At the same time, the system gain margin and phase margin were raised to 16.4 dB and 63°, respectively, with overshoot close to zero, effectively suppressing the accelerated aging caused by amplifier overload and frequent saturation.

In addition, the electromagnetic design of the motor itself can indirectly determine the number of touch-down impacts on the backup bearings and the overall safe operating time by influencing the rotor unbalance load. Chen et al. [35] performed multi-physics simulations on a bearingless permanent-magnet motor and showed that increasing the pole number from 4 to 10 makes the air-gap flux density distribution more uniform, reduces the eddy-current loss by approximately 60% on average, lowers the radial electromagnetic force ripple by 23–35%, and decreases the torque ripple by a factor of about 2.5. Such a multi-pole drive scheme with low torque ripple and low radial force ripple can reduce the dynamic load imposed on the backup bearings during long-term operation, thereby extending the trouble-free working time of the entire magnetically suspended flywheel assembly.

4.1.3. Summary of Long-Life Technologies

In summary, the approaches to achieving long service life in space inertial actuators diverge significantly according to bearing type. For mechanically bearing flywheels, life extension primarily relies on the synergy of three levels: ① optimization of Hertzian contact stress (e.g., through design of the groove curvature radius and preload) to reduce the accumulation rate of subsurface fatigue damage; ② an on-demand active lubrication system based on a piezoelectric micro-injection device embedded in the shaft system that replenishes fresh oil at the nanoliter level, ensuring that the elastohydrodynamic lubrication film parameter Λ remains above the safety threshold; and ③ degradation trend prediction based on deep state-space models or phase-space reconstruction networks, enabling a transition from "periodic open-loop maintenance" to "on-orbit condition-based oil replenishment." For magnetically suspended actuators, the core challenge for long life shifts to the long-term stability of the electromagnetic-electronic system: zero-power/low-bias-current control strategies (PDF + ZPI) reduce the steady-state bias current by approximately 80%, significantly lowering the thermal-aging rate of the power amplifier and coils; compact homopolar magnetic bearings and distributed hybrid magnetic bearings, by using permanent-magnet bias, control the steady-state levitation power consumption to the order of 1 W, further compressing the electro-thermal stress on power devices; a multi-pole (10-pole) bearingless motor design reduces the radial electromagnetic force ripple by 23–35%, thereby mitigating the dynamic impact of the drive end on the backup bearings; and on this basis, an improved CNN-LSTM composite degradation calibration network can track the multi-source degradation trajectories of current stiffness and power-amplifier gain in real time, providing an algorithmic foundation for the full-lifecycle digital twin of a magnetically suspended flywheel.

At present, mechanically bearing flywheels with active lubrication have demonstrated, in ground-based accelerated tests, a life potential equivalent to more than 15 years; however, the deployment of degradation prediction models in the resource-constrained onboard computing environment is still in the exploratory stage. Although magnetically suspended flywheels have already exhibited excellent low-vibration, long-life characteristics on several high-precision scientific satellites, the reliability of launch-lock mechanisms, the allowable number of rotors-drop impacts on backup bearings, and the miniaturization and radiation-hardening of control and power electronics remain the main bottlenecks constraining their large-scale application in low-cost constellations. In the future, integrating the low-power architecture of hybrid magnetic bearings, lightweight rotor topologies, and self-sensing degradation-compensation algorithms into a unified design framework holds the promise of achieving a better balance between long life and low disturbance, thereby meeting the demanding requirements for long-life inertial actuators in next-generation high-resolution remote sensing, space astronomy, and mega-constellation missions. As shown in Table 7.

Table 7. Key technologies for extending the service life of space inertial actuators.

Technology Route	Life-Determining Mechanism	Typical Lifetime Enhancement	Advantages	Current Main Limitations
Conventional oil-lubricated ball bearing + passive oil supply	Ability to maintain EHL film thickness	2×10^9 rev (≈8 yr LEO)	Simple structure, passive reliability	Oil film evaporation/migration leads to boundary lubrication failure
Ball bearing + active/ passive oil replenishment system	Actively maintaining oil supply, prolonging the period with $\Lambda > 1.5$	$>5 \times 10^9$ rev (>15 yr)	Significantly extends lubrication life; inherits mature bearing technology	Oil replenish-ment mecha-nism adds complexity
Active magnetic bearing (full AMB)	Contact-free, eliminates wear and lubrication	Theoretically unlimited	Zero friction, extremely low vibration	Complex 5-DOF control, high power consumption, single-point failure risk
Hybrid magnetic bearing (HMB)	PM bears static load; EM provides dynamic compensation	Near-unlimited, with reduced power consumption	Long life, low power consumption, high reliability	Weak shock resistance, launch-lock mechanism required

4.1.4. Comparative Summary of Key Long-Life Technologies

The long service life of space inertial actuators is not determined by a single factor; rather, it results from the coupled optimization of bearing lubrication, magnetic suspension, radiation-hardened electronics, and thermal-mechanical cycling. Table 8 summarizes the core mechanisms, lifetime potential, and engineering trade-offs of different technology routes.

Table 8. Comparative summary of key long-life technologies for space inertial actuators.

Technology Route	Life-Limiting Mechanism	Typical Lifetime Enhancement	Advantages	Main Current Limitations
Oil-lubricated ball bearing + passive oil supply	Maintenance of elastohydrodynamic film thickness	$\sim 2 \times 10^9$ rev ($\approx$8 yr LEO)	Simple structure, passive reliability	Film evaporation/migration leads to boundary-lubrication failure
Ball bearing + active/passive oil replenishment	Active maintenance of oil film ($\Lambda > 1.5$)	$>5 \times 10^9$ rev (>15 yr)	Simple structure, passive reliability	Film evaporation/migration leads to boundary-lubrication failure
Active magnetic bearing (full AMB)	Contact-free levitation; no wear or lubricant	Theoretically unlimited	Zero friction, extremely low vibration	Complex 5-DOF control, high power, single-point failure risk
Hybrid magnetic bearing (HMB)	PM takes static load; EM for dynamic stabilization	Near-unlimited, with reduced power	Long life, low power, high reliability	Low shock resistance; launch-lock required
Radiation-hardened electronics	TID/SEE protection	Enables 15 yr GEO/deep-space missions	Long life, low power, high reliability	Low shock resistance; launch-lock required

Conventional oil-lubricated ball bearings rely on vacuum-stable synthetic oils (e.g., MAC or PFPE) and optimized Hertzian contact stress to achieve a tribological life of approximately 2×10^9 rev. By incorporating active or passive supplementary oil-supply systems, the oil-film parameter Λ can be continuously maintained above 1.5, postponing the nominal lubrication failure threshold by a factor of 1.5–2.0 and extending the mechanical life beyond 5×10^9 rev—equivalent to a 15-year GEO mission.

Active magnetic bearings (AMBs) theoretically eliminate mechanical wear and lubricant loss, offering unlimited life. However, they require closed-loop stabilization in five degrees of freedom (5-DOF), and any single-point failure in the sensor-power-algorithm chain can trigger a "rotor drop" event. Furthermore, AMBs typically increase bus power consumption by 30–50% compared with mechanical bearings.

Hybrid magnetic bearings (HMBs) use high-coercivity permanent magnets to provide more than 80% of the static suspension force, reserving electromagnetic coils only for dynamic perturbation rejection. This architecture inherits the long-life advantage of magnetic levitation while substantially reducing steady-state power dissipation and thermal load, and it has become the mainstream solution in domestic Chinese engineering applications.

In summary, combining active oil-replenishment lubrication or hybrid magnetic suspension with radiation-hardened electronic systems currently represents the most viable path toward achieving an ultra-long service life (>15 years) for space inertial actuators. The former leverages mature bearing manufacturing and lubrication management, whereas the latter represents the frontier of friction-free actuation.

4.2. High-Precision Control

For missions requiring stringent attitude-control accuracy—such as inter-satellite optical communication and deep-space exploration—further improvement in dynamic response and torque-control precision is imperative. Enhancing the control performance of space inertial actuators depends primarily on advances in two domains: sensor technology and control algorithms.

4.2.1. Sensors

Conventional sensors used in harsh space environments include Hall-effect sensors, optical encoders, and resolvers. Hall-effect sensors offer high reliability but limited velocity-measurement accuracy; optical encoders provide superior accuracy but are susceptible to displacement effects and reduced reliability in high-orbit applications; and resolvers deliver excellent velocity accuracy and reliability, albeit with higher cost and mass.

With the rapid proliferation of large satellite constellations, space inertial actuators increasingly require sensors that combine high reliability with high precision. Recent advances by sensor manufacturers have improved Hall-effect speed-measurement accuracy by integrating magnetic-flux concentration with switched Hall technology.

For flywheels using conventional switched Hall control, steady-state speed-control accuracy is approximately ±0.5 rpm. By integrating magnetic-flux concentration with switched Hall technology, control accuracy can be improved to better than ±0.1 rpm, approaching the performance of optical encoders and resolvers.

4.2.2. Control Algorithm

Space inertial actuators must simultaneously achieve low torque ripple, disturbance rejection, vibration suppression, fault tolerance, and computational determinism within the radiation, power, and mass constraints of spaceborne embedded hardware. No single control paradigm satisfies all requirements simultaneously; practical implementations represent trade-offs among modeling completeness, computational burden, robustness to parameter variation, and flight qualification tractability. The following subsections review each principal control strategy against these five evaluation dimensions.

(i) Proportional–Integral and Proportional–Integral–Derivative Control

PI and PID regulators remain the most widely deployed flight-qualified strategies for reaction wheel speed and current loops because they impose minimal computational demands, two or three multiplications and additions per sample are fully compatible with anti-fuse FPGA implementations at 1–3 kHz sampling, require no system model, and can be tuned deterministically. Their primary limitation is weak disturbance rejection under nonlinear bearing friction and torque ripple: integral action compensates for constant disturbances but introduces phase lag at dynamic frequencies, and the proportional gain is bounded by actuator structural resonance. For conventional ball-bearing reaction wheels at moderate speed ranges, PI speed control achieves accuracy of approximately ±0.5 rpm, which is insufficient for sub-arcsecond pointing missions.

(ii) Active Disturbance Rejection Control and Linear Extended State Observer

ADRC treats all unmodeled dynamics, parameter perturbations, bearing-friction variation, torque ripple, and external disturbances as a generalized total disturbance state estimated by an LESO in real time. The LESO for an n-th-order plant augments the state vector by one disturbance state, yielding an (n + 1)-dimensional observer tuned by a single bandwidth parameter ω_0 that must satisfy ω_0 > 3–5 times the control bandwidth. Song et al. [36] demonstrated 40–60% overshoot reduction and sub-0.5 s settling time at 2000 rpm under a 0.1 N·m step disturbance. Zheng et al. [37] showed torque-ripple suppression from 8.0% to 1.5% of the command value using LESO-based friction compensation. Modeling requirements are minimal plant order and input gain only, but real-time discretization at 10 kHz demands DSP/ARM processors with hardware FPUs. TMR protection of observer states increases processor load by 30–50%.

(iii) Robust Control (H∞ and μ-Synthesis)

H∞ and μ-Synthesis methods design a fixed-gain controller that minimizes the worst-case gain from disturbance inputs to controlled outputs over a defined uncertainty set, providing guaranteed stability and performance across modeled uncertainty, including $\pm$30% bearing friction variation and $\pm$20% rotor inertia variation due to thermal expansion. The primary limitation is conservatism: the controller is optimized for the worst-case operating point and may underperform at nominal conditions. Computational cost of evaluation is low since the controller is a fixed-gain matrix, but the design phase requires a linear fractional transformation (LFT) model of the plant obtained through careful identification of friction nonlinearity and structural resonance frequencies. Flight qualification is tractable because the implemented structure is a fixed-gain linear filter fully compatible with anti-fuse FPGA hardware.

(iv) Adaptive Control (MRAC and Adaptive Feedforward Compensation)

Model reference adaptive control (MRAC) and adaptive feedforward compensation adjust controller parameters online in response to observed plant behavior, making them well-suited for tracking slowly time-varying bearing friction, lubricant viscosity changes, and rotor mass-property drift over mission lifetime. The stability requirement constrains the adaptation rate to remain below the closed-loop bandwidth to satisfy Lyapunov stability conditions. Adaptive friction compensation reduces speed-tracking error by 60–70% over the first 1000 h of in-orbit operation as bearing lubricant redistributes. The adaptation algorithm must incorporate parameter-projection mechanisms to prevent divergence during transient maneuvers. Flight qualification is complicated by the need to demonstrate bounded parameter convergence and stability across all operational scenarios within a finite test campaign.

(v) Sliding-Mode Control

Sliding-mode control (SMC) drives the system state to a sliding surface in finite time, providing theoretically perfect rejection of matched disturbances bounded by the switching gain. For reaction wheel speed control, SMC suppresses bearing-friction disturbances more aggressively than PID but generates chattering high-frequency switching of the control signal that excites structural modes and increases micro-vibration transmission to the spacecraft bus. Boundary-layer smoothing and super-twisting higher-order SMC formulations reduce chattering amplitude at the cost of reduced disturbance rejection bandwidth. Tang et al. [38] demonstrated neural-network-augmented SMC for magnetically suspended CMG radial translation control, achieving rotor displacement tracking errors below 5 µm during rapid gimbal transitions. Implementation requires the switching frequency to remain below one-fifth of the first structural mode to avoid exciting actuator resonances.

(vi) Model Predictive Control

MPC optimizes a finite-horizon cost function at each sample instant subject to state and input constraints, enabling explicit management of wheel speed saturation, torque limits, thermal boundaries, CMG singularity proximity, and angular momentum envelope simultaneously. For reaction wheel clusters, MPC-based torque allocation satisfies attitude control torque requirements, wheel-speed saturation, and momentum management targets within a unified framework. The primary implementation barrier is computational: solving a quadratic program at each 1–10 ms control cycle demands floating-point matrix operations that exceed anti-fuse FPGA capacity and challenge radiation-tolerant DSP processors. Explicit MPC precomputing the optimal control law as a piecewise affine function of the state—partially resolves online computational burden but requires offline storage of polytopic region boundaries that may exceed available flash memory on compact satellite platforms.

(vii) Data-Driven Control and Neural-Network-Based Compensation

Data-driven methods, including neural-network-based feedforward compensation and Gaussian process regression, learn the nonlinear mapping between actuator state and disturbance torque from operational data without requiring an explicit parametric model. Tang et al. employed a radial basis function neural network to estimate residual nonlinear force in a magnetically suspended CMG rotor after linear magnetic-bearing control, achieving estimation errors below 2% of rated force. Practical limitations for spaceborne applications are threefold: (i) flight data volumes for network training are unavailable until after extended in-orbit operation, requiring ground pre-training on test-bench data that may not reflect actual flight tribological and thermal conditions; (ii) interpretability and certification of neural network outputs for safety-critical attitude functions is not yet addressed by existing space qualification standards; and (iii) radiation-induced weight perturbation in SRAM-based neural network implementations constitutes a SEU vulnerability requiring dedicated protection.

(viii) Fault-Tolerant Control and Analytical Redundancy

Fault-tolerant attitude control encompasses fault detection and isolation (FDI) at the unit level and torque reallocation at the spacecraft level. Alidadi and Rahimi [39] demonstrated lubricant-decay fault isolation within 180 s using an adaptive particle filter applied to bearing temperature measurements. Olfe et al. [40] confirmed that a robust wheel-cluster controller recovers from single-wheel dropout within three orbital control cycles by redistributing the lost torque component among remaining functional wheels. Key design constraints are: detection latency (must be below the time for pointing error to exceed the mission threshold), false-alarm probability (must not trigger unnecessary safing during normal saturation transients), and reconfiguration transient magnitude (the attitude error spike during reallocation must remain within the payload recovery envelope). Data-assisted approaches can predict imminent failure and allow planned reallocation before failure onset, avoiding the transient associated with unplanned reconfiguration.

(ix) Vibration Feedforward Cancellation and Integrated Attitude–Vibration Control

Vibration feedforward cancellation uses a model of the disturbance force spectrum derived from rotor speed, imbalance estimates, and bearing defect frequencies to generate a compensating force command superimposed on the attitude control torque. When implemented in the magnetic-bearing force loop of an MSFW, feedforward cancellation reduces the imbalance harmonic at $n\Omega$ by 15–25 dB within the control bandwidth, as demonstrated on the China Space Station core module. Integrated attitude and vibration control treats the spacecraft flexible structure and actuator dynamics as a single coupled plant, designing a control law that simultaneously regulates attitude error and minimizes vibration transmission to the payload mounting interface. You et al. [41] showed that neglecting structural flexibility between the CMG gimbal frame and the satellite bus underestimates force transmission at 35–85 Hz by 6–12 dB, and that co-designed structural damping augmentation in conjunction with active gimbal control reduces payload pointing jitter by 8–12 dB in this band relative to a decoupled design.

To facilitate cross-comparison and algorithm selection for different mission classes, Table 9 summarizes the key characteristics of the control strategies discussed above. Evaluations are grouped according to required hardware capability, model dependence, disturbance rejection potential, current flight heritage, and principal limitations.

Table 9. Comparison of control strategies for space inertial actuators.

Control Strategy	Processor Capability Required	Model Dependency	Disturbance Rejection Ability	Flight Heritage/TRL	Main Limitations
PI/PID	Minimal (anti-fuse FPGA, 1–3 kHz sampling)	None	Weak; compensates only constant disturbances; phase lag at dynamic frequencies; steady-state accuracy $\approx \pm 0.5$ rpm	Flight-proven (highest maturity)	Insufficient for sub-arcsecond pointing; gain limited by structural resonances
ADRC/LESO	High (DSP/ARM with hardware FPU; 10 kHz loop; TMR adds 30–50% overhead)	Very low (plant order and input gain only)	Strong; treats all uncertain dynamics as lumped disturbance; torque ripple suppressed from 8% to 1.5% in lab tests	Laboratory validated (TRL 4–5)	Real-time discretization accuracy; increased processor load under EDAC protection
Robust (H∞/μ-synthesis)	Low for runtime (fixed-gain matrix, compatible with anti-fuse FPGA)	High at design stage (LFT model with uncertainty bounds)	Guaranteed worst-case attenuation, but conservative at nominal operating point	Flight-tractable design; limited flight examples for RW/CMG	Conservatism may under-utilize actuator capacity; model identification effort
Adaptive (MRAC/ adaptive feedforward)	Medium (online adaptation loop; parameter projection logic)	Reference model required	Effective for slow parameter drift (bearing friction, lubricant viscosity); speed tracking error reduced by 60–70% in ground tests	Limited flight heritage (stability proof complex)	Convergence guarantee across full mission life difficult to certify; possible divergence during transients
Sliding-mode (SMC)	Medium-high (switching law, higher-order SMO; must keep switching < 1/5 first structural mode)	Bound on matched disturbance needed	Excellent rejection of matched disturbances theoretically; chattering compromises vibration performance	Laboratory demo; limited space applications	Chattering excites structural modes and increases micro-vibration transmission
Model predictive (MPC)	High (real-time QP solver; explicit MPC requires extensive memory)	Full plant model with constraints	Moderate; can handle coupled limits but is limited by prediction accuracy; not primarily a high-bandwidth disturbance rejector	Rare in current space products	Computational load exceeds the capability of current rad-tolerant space processors
Data-driven/neural-network	Low online (feed-forward evaluation); high offline training	Learned from data (black-box)	Good for identifiable nonlinearities (e.g., residual force $\approx$ 2% of rated force)	Laboratory validation only	Interpretability and flight certification absent; SEU-induced weight perturbation risk; pre-flight data not fully representative
Fault-tolerant control (FDI + reallocation)	Medium (particle filter/observer; real-time torque redistribution)	Fault model or degradation signatures required	N/A (ensures attitude stability after actuator fault)	Simulation and limited flight software; unit-level FDI in development	Detection delay vs. false-alarm trade-off; re-configuration transient may exceed payload tolerance
Vibration feed-forward/Integrated attitude-vibration control	Low-medium (feed-forward filter; co-design needs coupled model)	Disturbance spectrum model; structural coupling model	Excellent at targeted harmonics (15–25 dB reduction on CSS core module)	Flight-proven on flagship platforms (CSS, some optical satellites)	Performance degrades if bearing wear or structural modes shift; requires accurate ground characterization

https://doi.org/10.3390/act15070399

4.3. High Torque Output

Constellation-level multi-satellite formations and orbital-transfer maneuvers require actuators capable of delivering substantial output torque. This demand necessitates the development of high-power-density, high-torque reaction wheels and large control moment gyroscopes (CMGs) for agile satellite maneuvering platforms. In recent years, major spacefaring nations have developed space inertial actuators with enhanced torque-output capabilities:

1. Germany has developed a large CMG with a maximum output torque of 700 N·m and a maximum angular momentum of 5000 N·m·s; its reaction-wheel products achieve a maximum output torque of 0.7 N·m and a maximum angular momentum of 68 N·m·s.
2. The United States has developed a large CMG with a maximum output torque of 680 N·m and a maximum angular momentum of 5000 N·m·s; its reaction-wheel products achieve a maximum output torque of 0.75 N·m and a maximum angular momentum of 150 N·m·s.
3. China has developed a large CMG with a maximum output torque of 200 N·m and a maximum angular momentum of 1500 N·m·s; its reaction-wheel products achieve a maximum output torque of 1.5 N·m and a maximum angular momentum of 125 N·m·s.

The primary advantage of high-torque space inertial actuators is their rapid maneuverability, which satisfies the fast-response requirements of agile satellite platforms.

Evaluation of the torque-to-mass ratio reveals a localized 50% deficit when domestic configurations are scaled against international equivalents. For example, the Honeywell HR12-25 provides a structural output efficiency of 0.057 N·m/kg, compared with 0.027 N·m/kg for domestic commercial counterparts, identifying motor stator slot-fill optimization and lightweight composite-rotor consolidation as key manufacturing bottlenecks.

Torque Density Design Methodologies

Improving torque density (output torque per unit mass) cannot rely simply on increasing current or magnet volume; it requires coordinated optimization at the electromagnetic topology, winding configuration, and rotor-structure levels. Table 10 summarizes the physical mechanisms and experimentally observed improvements of three representative design paths.

Table 10. Design routes for improving torque density of PM actuators.

Design Route	Key Technical Feature	Physical Mechanism	Quantified Improvement
Halbach array + slot-less winding	Multi-segment Halbach PMs; ironless stator; dual rotor	Enhanced air-gap flux density; significant reduction of back-iron saturation; elimination of cogging torque and stator iron loss	Back-iron saturation reduced ≈ 60%; 70 mNm·s at 280 g; peak flux linkage 1.2 mWb
Rotor "cut-inner-compensate-outer"	Material removed from inner disk and added to outer rim at constant inertia	Increase effective radius of gyration; improve energy storage per unit mass	Energy density +36.8%; mass −26.9%; peak stress < 1500 MPa
Multi-pole optimization	Increase pole number; optimize pole-arc coefficient	Smoother air-gap flux-density waveform; lower harmonic amplitude	Eddy-current loss −60%; radial force ripple −23–35%; torque ripple reduced by ~2.5×

(1) Halbach arrays and slot less windings

In conventional radial-flux machines, the rotor back-iron and stator core account for a large fraction of the inactive mass. Liu et al. [42] proposed an ultra-lightweight, dual-rotor, slot less PM motor for CubeSat reaction wheels, in which one rotor disk consists of an N = 3 Halbach array (0°, 45°, 90° segments) and the other disk serves as an iron back-iron. The self-shielding effect of the Halbach array significantly enhances the air-gap flux density while reducing the back-iron magnetic saturation by approximately 60%, allowing the back-iron plate to be almost eliminated. Within a Φ50 × 40 mm envelope, the motor delivers 70 mNm·s angular momentum and 7 mNm continuous torque; the complete wheel weighs only 280 g, yielding a torque density of 25 mNm/kg. This clearly demonstrates the advantage of Halbach arrays and slot less windings for lightweight, high-torque-density actuators.

(2) Flywheel rotor shape optimization

Rotor geometry also influences the effective torque density. Liu et al. proposed a "cut-inner-compensate-outer" diameter-expansion method for a solid-metal, constant-thickness disk operating at 60,000 r/min. By removing material from the inner region and adding it to the outer rim while keeping the moment of inertia constant, the energy density increased by 36.8% and the rotor mass decreased by 26.9%, with the maximum stress remaining below 1500 MPa [43]. This implies that, within the same safety margin, the electromagnetic torque can be more efficiently converted into angular-momentum accumulation, indirectly raising the effective torque density.

(3) Multi-pole designs and torque-ripple suppression

High torque density must also preserve torque smoothness. Appropriately increasing the pole count can improve the air-gap flux-density waveform and reduce harmonic-induced eddy-current losses and radial force fluctuations. Chen et al. [44] showed by simulation of a bearing less PM motor that increasing the pole number from 4 to 10 reduces eddy-current loss by about 60%, lowers radial force ripple by 23–35%, and decreases torque ripple by a factor of approximately 2.5. This provides design guidance for achieving smooth torque output in high-torque-density applications. As shown in Table 10.

These design methods are already being adopted in commercial reaction wheels and CMGs, and they represent the core technical means for closing the torque-to-mass ratio gap between domestic products and their international counterparts.

4.4. Low Disturbance Vibration

Micro-vibrations induced by space inertial actuators can degrade spacecraft pointing accuracy and stability. For satellites carrying high-precision payloads, optimizing micro-vibration characteristics during actuator operation is essential to minimizing adverse effects on payload performance.

4.4.1. Passive Damping

Conventional passive damping improves the micro-vibration performance of space actuators through the following approaches [45–47]:

1. Enhanced manufacturing precision: Static and dynamic imbalance are reduced to decrease micro-vibration amplitude at the nominal rotational frequency of the rotor.
2. Improved bearing-assembly design: Bearing design and manufacturing processes are improved to minimize bearing eccentricity, thereby reducing micro-vibration amplitudes at the fundamental and harmonic frequencies of the inner and outer bearing rings.

3. Dedicated vibration-damping devices: Specialized vibration-isolation mechanisms are incorporated to mitigate actuator-generated micro-vibrations.

4.4.2. Magnetic Suspension Technology and Vibration Isolation

In addition to passive damping techniques, magnetic suspension technology represents a paradigm shift for achieving ultra-low-disturbance environments. Magnetically suspended flywheels (MSFWs) and magnetically suspended control moment gyroscopes (MSCMGs) eliminate high-frequency micro-vibrations caused by ball-bearing surface defects and cage instability. More importantly, magnetic bearings enable active vibration control (AVC). By integrating high-speed sensors with advanced control algorithms, the system can dynamically adjust electromagnetic forces to compensate for residual rotor unbalance in real time. This active isolation capability allows the actuator to provide a near-silent platform, which is critical for spacecraft carrying high-resolution optical payloads or sensitive scientific instruments requiring sub-microradian pointing stability [48–50].

Disturbance vibration is a key factor affecting payload stability in high-precision pointing missions. As shown in Table 11, conventional bearing-based actuators exhibit significant harmonic disturbances in the 0–2000 Hz frequency band, with disturbance-force amplitudes reaching the 0.1 N level. In contrast, actuators using magnetic suspension technology can reduce such disturbances by two orders of magnitude through active vibration control (AVC). Experimental validation on China's high-resolution optical remote-sensing satellites and the China Space Station (CSS) core module confirms that magnetic suspension actuators operating within AVC loops can suppress high-frequency disturbances by multiple orders of magnitude, thereby maintaining payload pointing stability at the sub-microradian level. As shown in Table 11.

Table 11. Comparison Between Passive and Active Vibration Isolation.

Characteristic Index	Conventional Mechanical Flywheel (Passive Damping)	Magnetically Suspended Flywheel (Active Control)
High-frequency disturbance amplitude	10^{-1}~10^{-2} N	10^{-3}~10^{-4} N
Dominant disturbance frequency	Multiples and harmonics (varies with speed)	Extremely low (mainly from residual imbalance)
Vibration isolation efficiency	Effective at high frequencies (>50 Hz), amplified at low frequencies	Full-band active compensation, improved by ~20–40 dB

Although MSFWs offer substantial advantages by eliminating physical contact and mechanical friction while suppressing high-frequency micro-vibrations, several critical engineering trade-offs and space-deployment challenges have hindered their immediate large-scale industrial application:

(a) SWaP Cost and Control Complexity: Active magnetic bearings (AMBs) require closed-loop stabilization control in five degrees of freedom (5-DOF), necessitating dense eddy-current displacement sensor arrays, high-power amplifier stages, and multivariable decoupling algorithms. Compared with mechanical counterparts, this increases baseline power consumption by approximately 30–50%. Furthermore, aggressive high-speed gimbal or frame-deflection maneuvers can induce strong gyroscopic coupling and nutation cross-interference, potentially overloading the real-time control loops of the spacecraft's onboard computer.

(b) Reliability Hazards and Rotor Drop: Unlike passive mechanical bearings, an AMB operates at an inherently electromagnetically unstable equilibrium. Any single-point failure in the sensor system or power stage can cause transient loss of levitation, triggering a catastrophic "rotor drop" event. The high-speed rotor may collide with auxiliary backup bearings, generating severe localized contact stresses and friction-induced thermal gradients that pose a direct risk of mechanical seizure.

(c) Shock Resistance and Air-Gap Constraints: Under severe launch conditions (with random vibration levels exceeding 10 grms), the transient dynamic stiffness of an AMB is constrained by magnetic saturation limits. Because only a narrow physical air gap of 0.2–0.5 mm exists between the rotor and stator, the structure faces a high risk of frequent and intense physical impacts. This constraint makes launch survivability without an active launch-lock mechanism a fundamental barrier to space qualification.

To overcome these on-orbit qualification barriers, China's aerospace sector has systematically advanced in-orbit technology validation. Active magnetic suspension systems have accumulated flight heritage on China's high-resolution optical remote-sensing satellites, Shijian-series experimental platforms, and the China Space Station (CSS) core module. On these flagship platforms, magnetic suspension actuators operating within AVC loops have suppressed high-frequency disturbances by multiple orders of magnitude and maintained payload pointing stability at the sub-microradian level. Despite this substantial flight heritage, a major industrial challenge for domestic commercial enterprises remains the transition from customized prototype units for flagship missions to automated, low-cost, large-scale mass production for dense satellite constellations [49].

Although magnetically suspended actuators have accumulated successful flight heritage on flagship Chinese platforms, bridging the gap between low-volume bespoke customization and high-rate constellation validation requires comprehensive hardware-in-the-loop (HIL) ground-testing infrastructure. Before orbital insertion, verification of AVC loops and evaluation of micro-dynamic transmission boundaries under gyroscopic precession require high-fidelity laboratory replication of dynamic carrier environments. Contemporary testing methodologies address this challenge through semi-physical simulation of space inertial sensors using carrier-amplitude modulation techniques [50]. By deploying the carrier-amplitude modulation matrix onto multi-axis simulation carriers and air-bearing testbeds, engineers can isolate, modulate, and calibrate substructure micro-vibration crosstalk in magnetically levitated rotors under realistic dynamic scaling, providing a critical qualification tool for reducing launch-shock air-gap failure risks before mass production.

4.4.3. Multi-DOF Hybrid Isolation and Active Control—Case Studies

Beyond passive damping and pure magnetic-bearing isolation, recent research has increasingly focused on combining passive load-carrying/active cancellation hybrid platforms with multi-channel adaptive control to achieve broadband micro-vibration suppression from sub-Hertz to several hundred Hertz. Table 11 compares two representative schemes.

Case 1: Electromagnetic-spring 6-DOF isolation system

Xie et al. [51] proposed a 6-DOF isolation platform composed of four passive isolators and eight electromagnetic actuators to protect precision payloads against combined broadband and tonal excitation. The system dynamics were modeled using Hamilton's generalized variational principle, while the auxiliary stiffness of the diaphragm springs was analyzed via finite-element method; Coulomb friction in the actuators was explicitly included. In the control domain, independent modal filtering combined with velocity-acceleration feedback was adopted for broadband suppression, and a multi-channel adaptive harmonic canceller was introduced to eliminate discrete tones in the 20–50 Hz band. Experimental results show that the transmissibility at 2 Hz dropped from +13.6 dB (passive) to −16.0 dB (active), an attenuation of 96.7%, and over 95% attenuation was achieved across the entire 0–100 Hz band.

Case 2: Pneumatic-magnetic parallel ultra-low-frequency isolator

Li et al. developed an ultra-low-frequency isolation unit for large precision instruments based on a positive-stiffness air spring in parallel with a three-layer magnetic negative-stiffness mechanism. The resulting high-static-low-dynamic stiffness characteristic yielded a vertical natural frequency as low as 0.6 Hz and a passive attenuation of 40 dB at 10 Hz. Active control employed a discrete-time LQG controller, in which a Kalman filter estimated the platform velocity state and an optimal feedback law provided equivalent sky-hook damping. Experiments demonstrated a 79% reduction in velocity amplitude at the resonance, with the transmissibility remaining below 0 dB over the full 0.6–100 Hz band. As shown in Table 12.

Table 12. Comparison of typical active micro-vibration isolation schemes for space applications.

Scheme	Configuration and Actuation	Key Modeling Approach	Core Control Strategy	Main Performance	Experimental Results
EM-spring 6-DOF isolator	4 passive isolators + 8 EM actuators	Hamilton model; FEM of diaphragm springs; Coulomb friction	Modal filtering + velocity-acceleration feedback (broadband); multi-channel adaptive harmonic cancellation	Isolation onset $\approx$ 0.5 Hz; attenuation > 95% in 0–100 Hz	2 Hz resonance from +13.6 dB to −16.0 dB (96.7% reduction); 99% RMS acceleration attenuation under combined excitation
Pneumatic-magnetic parallel isolator	Air spring + 3-layer magnetic negative stiffness; EM motor	Air-spring adiabatic model; positive/negative stiffness parallel analysis	LQG (Kalman filter + optimal state feedback)	Natural frequency 0.6 Hz; 40 dB at 10 Hz; Full-band transmissibility < 0 dB	Velocity amplitude reduced 79%; resonance peak eliminated by active control

These two solutions represent the mainstream technology streams of “full 6-DOF active isolation with electromagnetic-spring platforms” and “ultra-low natural frequency passive support + active damping,” providing directly applicable engineering frameworks for micro-vibration isolation on high-resolution optical satellites and space telescopes.

4.5. Commercialization

4.5.1. System-Level Redundancy

In response to the demand for large satellite constellations, satellite launch volume is increasing rapidly. Cost reduction for space inertial actuators is therefore an inevitable trend in future development.

1. Iridium NEXT, the second-generation Iridium constellation launched between 2017 and 2019, followed a traditional aerospace design philosophy, with an estimated satellite cost of approximately US$45.45 million per unit.
2. Starlink satellites extensively use industrial-grade components combined with system-level redundancy and engineering optimization, achieving a balance between cost and reliability. Starlink V1.0, with reduced functionality, is estimated to cost between US$250,000 and US$500,000. The latest Starlink V3, featuring enhanced capabilities and greater channel capacity, costs approximately US$1.2 million—significantly less than traditional satellites.
3. With the full-scale deployment of China’s “GW” constellation and “G60/Qianfan” mega-constellation programs, the procurement paradigm for space actuators has shifted from small-scale customized production to high-frequency mass delivery. To balance performance limits with aggressive cost-reduction targets, China’s commercial aerospace enterprises have pioneered a distinctive cost-control technology roadmap based on three key dimensions.

First, at the component level, cost reductions are achieved through the substitution of commercial off-the-shelf (COTS) components. Traditional high-reliability aerospace-grade chips are being replaced by high-performance automotive-grade components. To mitigate the increased risk of single-event upsets (SEUs) in low Earth orbit (LEO), hardware fault-tolerance frameworks, such as triple modular redundancy (TMR) and Error Detection and Correction (EDAC) algorithms, are integrated into the control logic. This approach has reduced the hardware cost of the control core by more than 80%.

Second, at the structural level, optimization is achieved through integration of drive and control functions. By embedding the brushless DC motor stator, lightweight wheel hub, and drive electronics within a single housing, the system eliminates traditional external wiring harnesses and bulky connectors, thereby reducing machining complexity and assembly labor.

Third, at the manufacturing process level, design for manufacturing (DFM) is actively promoted. Advanced production facilities are incorporating automated dynamic-balancing machines and batch-operated vacuum thermal-cycling chambers to replace lengthy manual fine-tuning processes that formerly depended on highly skilled technicians. This transition converts traditional craftsmanship into standardized pulse-flow assembly-line production, enabling annual manufacturing capacity to exceed 3000 actuators.

The significant disparity in spacecraft-level costs between traditional platforms and contemporary low-Earth-orbit (LEO) constellations is rooted in differences in component-level and unit-level design paradigms. Traditional platforms, such as Iridium NEXT, incur high financial costs because each inertial actuator must achieve absolute hardware-level reliability, resulting in reliance on small-batch space-grade components and exhaustive unit-level testing. Conversely, the cost reductions achieved by Starlink and modern domestic constellations, such as “GW” and “Qianfan,” arise from the direct translation of system-level architectural choices—including tolerance of random single-unit failures and spacecraft-level networked redundancy—into the design specifications of the actuators themselves, as shown in Table 13.

Table 13. Technical Roadmaps for Cost Reduction in Commercial Space Actuators.

Cost-Reduction Dimensions	Traditional Aerospace Model	Low-Cost Pathways for Commercial Spaceflight	Cost Reduction Effects and Engineering Trade-Offs
Component selection	Aerospace-grade, anti-fuse hardened, custom components	Industrial-grade automotive-grade (COTS) components with fault-tolerant design	Chip and circuit costs reduced by over 80%; higher SEU software fault tolerance required.
Manufacturing and assembly	Precision CNC machining and skilled manual assembly	Modular design, automated adhesive dispensing, and mass production	Labor time per unit reduced by 70%; requires a strong focus on design-for-manufacturability.
Testing and screening	Stringent unit-level environmental stress screening	Matrix-based environmental testing and rapid board-level screening	Testing time and energy costs are reduced by 50–60%; it relies on spacecraft-level redundancy.

This quantitative relationship and engineering boundary, which directly links system-level trade-offs with fundamental changes in actuator technology, is systematically summarized in Table 8. Through the paradigm shift from “radiation-hardened hardware” to “software-defined reliability,” modern space actuators have evolved from highly customized, expensive specialized instruments into standardized, cost-effective industrial products, thereby becoming a pivotal factor in reducing the total lifecycle cost of spacecraft.

4.5.2. Global Private-Sector Matrix and Paradigm Disruption

The global New Space supply chain is undergoing profound structural disruption driven not only by flagship constellation operators but also by agile private-sector startups and commercial component suppliers. Noteworthy international companies, including

Blue Canyon Technologies, Rocket Lab (Sinclair Interplanetary), and CubeSpace, have shifted from traditional low-volume customized manufacturing toward modular, plug-and-play attitude control architectures. Key industrial trends pioneered by these private startups include monolithic attitude control system (ACS) clusters, which consolidate orthogonal reaction-wheel configurations, drivers, and localized processing loops into a single mechanical chassis, and structural integration, in which actuators are embedded directly into the load-bearing satellite frame to maximize internal payload volume.

Alongside these international advances, emerging domestic commercial space enterprises in China, such as Hunan Lanyue and Beijing Yidong Aerospace, are establishing high-rate manufacturing infrastructure to support extensive LEO constellation networks. As outlined in Table 9, this private-sector paradigm shift prioritizes software-defined performance configurations over rigid hardwired setups, allowing a single standardized hardware platform to accommodate multiple satellite mass classes through orbital software updates. By combining automotive-grade component qualification with automated robotic dynamic-balancing lines, these private enterprises have transformed space actuators from high-cost, single-unit bespoke instruments into mass-producible, cost-effective commercial commodities, as shown in Table 14.

Table 14. Emerging Private-Sector Innovations and Commercial Space Disruption Matrix.

Emerging Private Startup Paradigm	Key Technical Innovation/Design Vector	System-Level Industrial Benefit	Commercial Representative Examples
Monolithic ACS Clusters	Consolidate multiple reaction wheels, drivers, and micro-controllers into a single sub-assembly with unified telemetry interfaces.	Reduces assembly and integration timelines, minimizes cable errors, and lowers satellite bus overhead.	Cube Space (Modular cubes), Blue Canyon Technologies (Flex core integrated ACS architectures).
Software-Defined Performance Ceilings	Use COTS chips with adaptive software to adjust operational limits based on real-time telemetry.	Enables standardization, allowing a single actuator to adapt via OTA or orbital updates.	Rocket Lab/ Sinclair Interplanetary, Hunan Lanyue (Programmable wheels).
Robotic Dynamic Tuning & DFM	Employ machine-vision robotic balancing and automated environmental testing.	Transitions manufacturing from artisanal craft to automotive-style assembly, ensuring high consistency.	Beijing Institute of Control Engineering (Production base), Rocket Lab, Beijing Yidong Aerospace.

In summary, the commercialization of space actuators is reshaping the satellite technology landscape by reducing costs while improving reliability and performance. This transformation is essential for future large-scale satellite networks and will require continuous innovation and adaptation by both established aerospace organizations and emerging commercial enterprises.

4.6. Spacecraft-Level Integrated Attitude Control and Fault-Tolerant Operation

Space inertial actuators should be evaluated not only as independent electromechanical units, but also as coupled components of the spacecraft attitude determination and control system. The final pointing performance of a spacecraft depends on the interaction among actuator dynamics, spacecraft rigid-body motion, structural flexibility, sensor feedback, control allocation, momentum management, and payload disturbance sensitivity. For reaction wheel systems, major spacecraft-level constraints include wheel saturation, momentum unloading, torque ripple, rotor imbalance, bearing degradation, and single-wheel failure. For CMG systems, additional challenges arise from gimbal singularities, steering-law design, gyroscopic coupling, gimbal structural stiffness, and high-frequency disturbance transmission.

Fault-tolerant attitude control is therefore essential for long-duration and high-reliability missions. When an actuator degrades or fails, the spacecraft controller must redistribute torque commands among the remaining actuators while satisfying speed, torque, angular momentum, voltage, thermal, and pointing constraints. Observer-based fault diagnosis, analytical redundancy, reconfigurable control, constrained control allocation, and data-assisted fault estimation provide effective approaches for maintaining attitude stability under actuator faults. However, their flight application requires careful validation because fault detection must respond rapidly enough to protect pointing accuracy while avoiding false alarms during transient maneuvers, external disturbances, or normal actuator saturation.

Integrated attitude and vibration control is also becoming increasingly important for high-resolution optical remote sensing, astronomical observation, and inter-satellite laser communication missions. Periodic disturbances generated by wheels, CMGs, bearings, motors, and drive electronics can propagate through flexible spacecraft structures and degrade payload line-of-sight stability. Disturbance observers, feedforward cancellation, notch filtering, wheel-speed scheduling, active vibration isolation, and coupled attitude-vibration control can reduce these effects, but their effectiveness depends on accurate disturbance modeling and ground validation under realistic structural boundary conditions. Future research should therefore shift from unit-level actuator optimization toward actuator-spacecraft co-design, in which mechanical design, embedded control, fault tolerance, vibration suppression, and payload pointing requirements are considered within a unified system framework.

4.6.1. Redundant Actuator Fault Reconfiguration—A Satellite Case Study

Fault-tolerant control of redundant actuators requires the control system to instantaneously and safely redistribute torque commands among the remaining healthy units after a partial failure. Zhang et al. [52] provided an operational engineering solution based on a coupled thruster layout for an eight-thruster spacecraft, the core concept of which can be directly extended to inertial actuator clusters.

On-orbit fault-reconfiguration example: In this spacecraft, eight thrusters were mounted obliquely (each thrust line inclined at 45° relative to the body axes) so that every thruster simultaneously generated torque components about all three axes. A pre-compiled fault-to-allocation look-up logic table was stored onboard. During operation, if Thruster #1 (responsible for yaw control) fails due to a stuck valve, the system instantaneously switches to the allocation logic in Table II of [52], assigning the required yaw torque to Thrusters #2, #5, #7, etc. When Thruster #5 subsequently fails as well, the system re-routes the commands according to the dual-fault allocation Table IV of [52], still maintaining full three-axis attitude control. Probability calculations show that, for a single-thruster failure probability of 3%, the fault-tolerant probability of the coupled allocation scheme reaches 98.98%, whereas the traditional decoupled layout achieves only 88.22%.

Although this case study uses thrusters, the philosophy of "physical cross-coupled configuration plus logical decoupled allocation" is fully applicable to non-orthogonal reaction wheel or CMG clusters. In practice, more general methods employ on-line optimization-based allocation (e.g., pseudo-inverse, linear programming, or quadratic programming) that, combined with fault-diagnosis information, solves the optimal torque distribution in real time while satisfying speed, torque, power, and thermal constraints.

4.6.2. Comparison of Control Allocation Strategies

Below is Table 15, which compares control allocation strategies for redundant actuators.

https://doi.org/10.3390/act15070399

Table 15. Comparison of control allocation strategies for redundant actuators.

Strategy	Actuator Configuration	Reconfiguration Method	Fault-Tolerance Capability	Computational/ Implementation Complexity
Traditional decoupled allocation	Orthogonal mounting; each actuator controls a single axis	Relies on per-axis cold backup	Single-point failure causes loss of one axis control	Very low
Coupled allocation (off-line look-up table)	Non-orthogonal mounting; individual actuator generates multi-axis torques	Pre-stored fault-to-allocation table; online table lookup	Tolerates 1–4 actuator failures; fault-tolerant probability 98.98%	Low
Adaptive fault compensation + simple redistribution	Conventional orthogonal or skewed	Online estimation of loss-of-effectiveness factor; tasks redistributed after failure isolation	Effective for gradual efficiency loss; sudden failure requires backup wheels	Medium (online estimation)
Online optimization-based allocation (QP/LP)	Any redundant configuration	Constrained optimization solved at each control cycle	Theoretically full-fault reconfiguration; depends on accurate fault model	High (requires real-time solver)

5. Conclusions

This review has systematically examined recent advances and development trends in space inertial actuators, with emphasis on reaction wheels, momentum wheels, flywheels, and control moment gyroscopes used in spacecraft attitude-control systems. By integrating peer-reviewed academic literature with representative industrial product data, the paper shows that actuator development is no longer determined solely by single-unit torque or angular-momentum capacity. Instead, future performance depends on the coupled optimization of rotor structure, bearing support, lubrication, magnetic suspension, motor-drive design, embedded electronics, control algorithms, micro-vibration suppression, reliability assurance, and spacecraft-level attitude-control architecture.

The comparative analysis identifies five interrelated development directions, further shaped by spacecraft-level integration and fault-tolerant operation. First, long service life remains a central requirement, especially for high-value remote-sensing, communication, deep-space, and long-duration orbital missions. Bearing wear, lubricant degradation, radiation effects, and thermal-vacuum cycling remain key lifetime-limiting mechanisms. Second, high-precision control increasingly depends on the co-design of sensors, motor drives, radiation-tolerant embedded processors, and advanced control algorithms. Third, high torque and angular-momentum density require improvements in electromagnetic loading, structural integration, thermal management, and CMG gimbal dynamics. Fourth, low-disturbance operation has become essential for high-resolution optical payloads and laser communication missions, making micro-vibration modeling, passive damping, active vibration isolation, and magnetic suspension critical research priorities. Fifth, commercial constellation deployment is shifting actuator design from low-volume customized manufacturing toward modular, standardized, high-rate, and cost-effective production.

Overall, the development of space inertial actuators is moving from component-level performance improvement toward system-level co-design. Product specifications provide useful engineering benchmarks, but academic research is necessary to explain the modeling assumptions, disturbance mechanisms, control limitations, failure modes, and qualification constraints underlying these products. Future research should therefore strengthen the connection between actuator hardware design, embedded control, fault-tolerant operation, vibration suppression, and spacecraft-level attitude performance. Such an integrated approach will be essential for achieving high reliability, high pointing accuracy, low disturbance, and scalable manufacturing in the next generation of spacecraft attitude-control systems.

https://doi.org/10.3390/act15070399

(1) Outstanding Challenges and Future Research Priorities

Despite the substantial progress identified in the five development trends, several critical engineering and scientific gaps remain that must be addressed to achieve the full potential of next-generation space inertial actuators.

(2) Standardization of lubrication life-test methodologies.

The lifetime of oil-lubricated ball bearings remains the single largest factor limiting actuator service life, yet no universally accepted accelerated life-test protocol exists that quantitatively correlates ground vacuum-thermal cycling results with on-orbit oil-film degradation. Developing such a standard—together with validated models for lubricant evaporation, migration, and replenishment in microgravity—would enable consistent certification of 15- to 20-year lifetimes across manufacturers and mission classes.

(3) Launch survivability and touchdown protection of narrow-gap magnetic bearings.

Hybrid and active magnetic bearings have demonstrated transformative vibration performance in orbit, but their 0.2–0.5 mm air gaps remain highly vulnerable during launch vibration. A flight-qualified, lightweight launch-lock or backup-bearing mechanism that can repeatedly survive impact without debris generation, cold-welding, or excessive stiffness injection has yet to reach industrial maturity. This is currently the single most critical barrier to the large-scale commercial adoption of magnetically suspended actuators.

(4) High-performance radiation-tolerant embedded processors.

Advanced observer-based, adaptive, and data-driven control strategies offer clear performance gains but demand floating-point throughput far beyond what current anti-fuse FPGAs can deliver. There is a pressing need for space-grade processors that combine >100 DMIPS performance, hardware floating-point support, and radiation-hardening-by-design (RHBD) with manageable power consumption, so that complex real-time algorithms can co-exist with TMR and EDAC overheads.

(5) Autonomous in-orbit adaptation of micro-vibration isolation systems.

Active vibration isolation platforms have been demonstrated on flagship spacecraft, but they operate with ground-tuned, fixed-parameter controllers. In practice, spacecraft structural dynamics evolve during the mission owing to propellant depletion, thermal deformation, and payload operations. Achieving fully autonomous, in-orbit adaptive tuning of wideband isolation systems—without risking instability—remains an open challenge that is essential for future high-resolution optical and interferometric missions.

(6) Statistical reliability frameworks for COTS-based mass manufacturing.

The shift from radiation-hardened custom components to automotive-grade COTS devices, combined with assembly rates of thousands of actuators per year, demands a new statistical quality-control paradigm. Current qualification methodology, based on exhaustive unit-level screening, is incompatible with constellation-scale production. Research is urgently needed on radiation-response variability modeling, lot-acceptance strategies, and in-line automated health monitoring that together guarantee software-defined reliability without heritage-level testing.

Addressing these five challenges will require integrated efforts across tribology, mechatronics, radiation physics, control theory, and industrial engineering. Progress in these areas will directly determine whether the next generation of space inertial actuators can simultaneously satisfy the requirements of long service life, ultra-high precision, high torque density, ultra-low disturbance, and scalable low-cost production.

Author Contributions: Conceptualization, H.Z. and X.W.; methodology, H.Z.; validation, L.Y.; formal analysis, H.Z.; investigation, L.Y.; resources, X.W. and H.W.; data curation, Z.Y. and Z.F.; writing—original draft preparation, H.Z.; writing—review and editing, X.W.; supervision, X.W.; project administration, H.W.; funding acquisition, X.W. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Aero Science Foundation of China, grant number 20240007069003.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors on request. The original contributions presented in the study are included in the article. Further inquiries can be directed to the corresponding authors.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Lappas, V.; Richie, D.; Hall, C.; Fausz, J.; Wilson, B. Survey of technology developments in flywheel attitude control and energy storage systems. *J. Guid. Control Dyn.* **2009**, *32*, 354–365. [CrossRef]
2. Mumm, E.; Davis, K.; Mahin, M.; Neal, D.; Hayes, R. Miniature control moment gyroscope development. In Proceedings of the 2014 IEEE Aerospace Conference, Big Sky, MT, USA, 1–9 March 2014; pp. 1–9.
3. Mkrtychyan, A.R.; Bashkeev, N.I.; Yakimovskii, D.O.; Akashev, D.I.; Yakovets, O.B. Control moment gyroscopes for spacecraft attitude control systems: Current status and prospects. *Gyroscopy Navig.* **2015**, *6*, 236–240. [CrossRef]
4. Mehrjardi, M.F.; Sanusi, H.; Ali, M.A.M. Developing a proposed satellite reaction wheel model with current mode control. In Proceedings of the 2015 International Conference on Space Science and Communication (IconSpace), Malacca, Malaysia, 10–12 August 2015; pp. 410–413.
5. Sorokin, A.V.; Yaremenko, V.V. Control moment gyroscopes for spacecraft attitude control systems: History of development. *Gyroscopy Navig.* **2022**, *13*, 53–58. [CrossRef]
6. Keele, S. Guidelines for Performing Systematic Literature Reviews in Software Engineering Technical Report; EBSE Technical Report EBSE-2007-01. 2007, pp. 1–57. Available online: https://www.researchgate.net/profile/Barbara-Kitchenham/publication/302924724_Guidelines_for_performing_Systematic_Literature_Reviews_in_Software_Engineering/links/61712932766c4a211c03a6f7/Guidelines-for-performing-Systematic-Literature-Reviews-in-Software-Engineering.pdf (accessed on 8 May 2026).
7. Page, M.J.; McKenzie, J.E.; Bossuyt, P.M.; Boutron, I.; Hoffmann, T.C.; Mulrow, C.D.; Shamseer, L.; Tetzlaff, J.M.; Akl, E.A.; Brennan, S.E.; et al. The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *PLoS Med.* **2021**, *18*, e1003583. [CrossRef] [PubMed]
8. Snyder, H. Literature review as a research methodology: An overview and guidelines. *J. Bus. Res.* **2019**, *104*, 333–339. [CrossRef]
9. NASA. State-of-the-Art of Small Spacecraft Technology–Guidance, Navigation and Control (Reaction Wheels). NASA Small Spacecraft Technology Program. Available online: https://www.nasa.gov/smallsat-institute/ (accessed on 1 May 2026).
10. Honeywell Aerospace–Reaction Wheel Assemblies. Available online: https://www.honeywellaerospace.com/us/en/products-and-services/products/emerging-technologies/space/space-sensors/hr04-hc7-and-hc9-reaction-wheel-assemblies (accessed on 1 June 2021).
11. Chen, T.; Wen, H.; Hu, H.; Jin, D. On-orbit assembly of a team of flexible spacecraft using potential field-based method. *Acta Astronaut.* **2017**, *133*, 221–232. [CrossRef]
12. Carrara, V.; Kuga, H.K. Estimating Friction Parameters in Reaction Wheels for Attitude Control. *Math. Probl. Eng.* **2013**, *8*, 249674. [CrossRef]
13. Lottes, L.M.; Kaiser, N.; Goossens, N.; Oelze, H.W.; Braxmaier, C. Topology optimization of an additive manufactured reaction flywheel designed for an Earth-observation satellite. *CEAS Space J.* **2021**, *13*, 521–532. [CrossRef]
14. Narkiewicz, J.; Sochacki, M.; Zakrzewski, B. Generic Model of a Satellite Attitude Control System. *Int. J. Aerosp. Eng.* **2020**, *17*, 5352019. [CrossRef]
15. Airbus Establishment, Expansion into Defense, Space, and Helicopters. Available online: https://www.airbus.com/en (accessed on 1 February 2026).
16. Gaude, A.; Lappas, V. Design and Structural Analysis of a Control Moment Gyroscope (CMG) Actuator for CubeSats. *Aerospace* **2020**, *7*, 55. [CrossRef]
17. Platonov, V.N.; Sumarokov, A.V. Studying the possibility of ensuring the stabilization accuracy characteristics of an advanced spacecraft for remote sensing of the Earth. *J. Comput. Syst. Sci. Int.* **2018**, *57*, 655–665. [CrossRef]
18. Platonov, V.N.; Sumarokov, A.V. Controlling a satellite using single-gimbal control moment gyroscope during their spinning and braking. *J. Comput. Syst. Sci. Int.* **2020**, *59*, 289–300. [CrossRef]
19. Comat Aerospace Official History Page. Available online: https://comat.space/p/small-sat/fr-rw-technology/ (accessed on 1 May 2021).

20. Cui, P.; Yan, N. Research on Modeling of the Agile Satellite Using a Single Gimbal Magnetically Suspended CMG and the Disturbance Feedforward Compensation for Rotors. *Sensors* **2012**, *12*, 16964–16987. [CrossRef] [PubMed]
21. Kul'ba, V.V.; Mikrin, E.A.; Pavlov, B.V.; Platonov, V.N. *Teoreticheskie osnovy proektirovaniya informatsionno-upravlyayushchikh system kosmicheskikh apparatov (Theoretical Fundamentals of Designing Spacecraft Information and Control Systems)*; Nauka: Moscow, Russia, 2006.
22. Facchino, M.; Totsuka, A.; Capello, E.; Satoh, S.; Guglieri, G.; Yamada, K. Design and validation of an MPC controller for CMG-based testbed. *Optim. Eng.* **2023**, *24*, 185–221. [CrossRef]
23. Hou, Y.; Wang, C.; Duan, P.; Yu, H.; Zhao, X.; Chen, S.; Zhang, L. A General Method to Obtain the Frequency Response Function from the Disturbance Source to the Sensitive Payload. *Appl. Sci.* **2023**, *13*, 4844. [CrossRef]
24. Zhang, T.; Ferguson, P. Optimal Reaction Wheel Control with Stiction and Resonance Avoidance. In *Space Operations. Springer Aerospace Technology*; Cruzen, C., Schmidhuber, M., Lee, Y.H., Eds.; Springer: Cham, Switzerland, 2022. [CrossRef]
25. Robert, J. Bauer, Kinematics and dynamics of a double-gimbaled control moment gyroscope. *Mech. Mach. Theory* **2002**, *37*, 1513–1529. [CrossRef]
26. Li, J.; Post, M.; Wright, T.; Lee, R. Design of Attitude Control Systems for CubeSat-Class Nanosatellite. *J. Control Sci. Eng.* **2013**, *15*, 657182. [CrossRef]
27. Ravichandran, M.H.; Achari, V.T.S.; Joseph, C.C.; Devasahayam, R. Design analysis and development of halbach array PMBDC motor for torquing the gimbal of control Moment Gyroscope. *J. Spacecr. Technol.* **2010**, *20*, 51–55.
28. Ye, T.; Pang, H.; Zhou, Y.; Liu, S. Simulation Method for Contact Stress of Aerospace Mechanism Bearing Based on Nonlinear Dynamic Model. In Proceedings of the 2022 Global Reliability and Prognostics and Health Management (PHM-Yantai), Yantai, China, 13–16 October 2022; pp. 1–6. [CrossRef]
29. Li, K.; Liu, Y.; Liu, J.; Chen, W. Study on the Performance of a Designed Annular Piezoelectric Microjet for Active Lubrication of Space Bearing. *IEEE Trans. Ind. Electron.* **2022**, *69*, 2728–2736. [CrossRef]
30. Hu, Y.; Fang, X.; Lin, X.; Tong, J.; Zhang, F.; Huang, P. Deep Network-Driven State Space Modeling for Rolling Bearing Degradation Prediction. In Proceedings of the 2025 International Conference on Equipment Intelligent Operation and Maintenance (ICEIOM), Urumqi, China, 1–3 August 2025; pp. 635–639. [CrossRef]
31. Li, Z.; Xin, G.; Qin, Y. Health State Prediction of Rolling Element Bearing Using Phase Space Reconstruction and Improved GMDH. In Proceedings of the 2020 International Conference on Sensing, Diagnostics, Prognostics, and Control (SDPC), Beijing, China, 5–7 August 2020; pp. 371–375. [CrossRef]
32. Cheng, Y.; Jiang, F.; Chen, Q.; Peng, C. Study on Performance Degradation Tracking of Magnetically Suspended Flywheels Based on an Improved CNN-LSTM Calibration Network. In Proceedings of the 2025 4th International Symposium on Aerospace Engineering and Systems (ISAES), Nanjing, China, 25–27 July 2025; pp. 84–88. [CrossRef]
33. Krishnan, S.; Harikrishnan, A.; Kumar, A.S.; Ravichandran, M.H. Design of a Novel Four DOF Active Magnetic Bearing for Space Applications. In Proceedings of the 2022 IEEE International Conference on Power Electronics, Drives and Energy Systems (PEDES), Jaipur, India, 14–17 December 2022; pp. 1–5. [CrossRef]
34. Ratheesh, K.; Kaarthik, R.S.; Sam, D.D.D. Pseudo Derivative Feedback (PDF) Control for Performance Improvement in Magnetic Bearing of Reaction Wheels. In Proceedings of the 2022 IEEE International Conference on Power Electronics, Drives and Energy Systems (PEDES), Jaipur, India, 14–17 December 2022; pp. 1–6. [CrossRef]
35. Hsiao, D.-C.; Hsieh, M.-F. Design and Implementation of Novel Homopolar Magnetic Bearings Incorporated in Reaction Wheel for Satellite Attitude Control. *IEEE Access* **2023**, *11*, 66374–66381. [CrossRef]
36. Song, J.; Guo, J.; Qin, C.; Zhao, W. The Design of a Reaction Flywheel Speed Control System Based on ADRC. *Automation* **2023**, *4*, 246–262. [CrossRef]
37. Zheng, S.; Hao, M.; Mao, K.; Ma, W.; Yan, Y.; Qu, J. Torque Ripple Minimization of Reaction Flywheel Based on Linear Extended State Observer. *IEEE Trans. Ind. Appl.* **2025**, *71*, 1145–1154.
38. Tang, J.; Zhang, M.; Cui, X.; Sun, J.; Zhou, X. Neural network sliding model control of radial translation for magnetically suspended rotor (MSR) in control moment gyro. *Actuators* **2023**, *12*, 217. [CrossRef]
39. Alidadi, M.; Rahimi, A. Fault diagnosis of lubrication decay in reaction wheels using temperature estimation and forecasting via enhanced adaptive particle filter. *Sensors* **2023**, *23*, 1474. [CrossRef] [PubMed]
40. Olfe, K.; Bello, A.; Fernandez, J.; Rodriguez, J.; Lapuerta, V. Design and experimental verification of a robust control to avoid individual calibration of multiple reaction wheels in satellites. *Adv. Space Res.* **2025**, *75*, 767–778. [CrossRef]
41. You, J.; Zhu, W.; Wang, H. Research on Microvibration Transmission of Control Moment Gyro Considering Internal Structural Flexibility. *Int. J. Aerosp. Eng.* **2025**, *2025*, 8885019. [CrossRef]
42. Liu, N.-W.; Hung, K.-Y.; Lyu, B.-T.; Yang, S.-C. Ultra-Light Reaction Wheel with Dual-layer rotor and Single-side Halbach Magnet Array for CubeSat. In Proceedings of the 2023 IEEE Energy Conversion Congress and Exposition (ECCE), Nashville, TN, USA, 20–24 October 2023; pp. 4365–4369. [CrossRef]

43. Li, H.; Yu, J. Anti-Disturbance Control Based on Cascade ESO and Sliding Mode Control for Gimbal System of Double Gimbal CMG. *IEEE Access* **2020**, *8*, 5644–5654. [CrossRef]
44. Cui, Y.; Zhu, Y.; Meng, Y.; Zhu, B.; Xie, Y.; Zhang, J. Fixed-Time Disturbance Observer-Based Composite Controller for CMG Gimbal Servo Systems With Prescribed Performance. *IEEE Trans. Aerosp. Electron. Syst.* **2026**, *62*, 10863–10872. [CrossRef]
45. Wu, D.; Xie, T.; Lu, M.; Li, G.; Lai, L.; Yang, Y.; Wang, H. Modeling and experimental study on the micro-vibration transmission of a control moment gyro. *IEEE Access* **2019**, *7*, 80633–80643. [CrossRef]
46. Abdelmaksoud, S.I.; Al-Mola, M.H.A.; Mohamed, S.H. Wheels in Space: Modeling and Comparative Control Analysis of a Reaction Wheel Pendulum for Space Attitude Stability. In Proceedings of the 2025 International Telecommunications Conference (ITC-Egypt), Alexandria, Egypt, 22–24 July 2025; pp. 649–654.
47. Xiang, B.; Liu, H.; Yu, Y. Gimbal effect of magnetically suspended flywheel with active deflection of Lorentz-force magnetic bearing. *Mech. Syst. Signal Process.* **2022**, *173*, 109081. [CrossRef]
48. Zhang, Z.; Pan, Y.; Zi, Z.; Xie, Y.; Zhao, W.; Zhang, J.; Zhang, H. Current Differential Signal Extraction Algorithm via Fast-TD and Its Application in Open-Circuit Fault Diagnosis of Magnetic Bearings. *IEEE Trans. Instrum. Meas.* **2025**, *74*, 3520811. [CrossRef]
49. Hsiao, D.C.; Hsieh, M.F. Integrated design and power loss minimization of the reaction wheel motor for satellite attitude control. *IEEE Trans. Ind. Appl.* **2023**, *59*, 3291–3299. [CrossRef]
50. Liu, Z.; Bai, Y.; Hu, M. Semiphysical simulation of space inertial sensor utilizing carrier amplitude modulation. *IEEE Sens. J.* **2025**, *25*, 8407–8416. [CrossRef]
51. Jing, Y.; Xiaoping, S.; Long, L.; Hailong, L. Nonlinear observer based time delay fault-tolerant attitude control for flexible spacecraft during orbit maneuver. In Proceedings of the The 27th Chinese Control and Decision Conference (2015 CCDC), Qingdao, China, 23–25 May 2015; pp. 2789–2793. [CrossRef]
52. Zhang, F.; Tang, Q.; Wang, Z.; Li, Y. Spacecraft Fault-Tolerant Attitude Control Thruster Layout Scheme. In Proceedings of the 2020 China Automation Congress (CAC 2020), Shanghai, China, 6–8 November 2020; pp. 3863–3866. [CrossRef]