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Recent advances in spacecraft dynamics and control

Lincheng LI[1], Ming XU[1*], Guang MENG[2], Dayi WANG[3] & Wei WANG[4*]

[1]*School of Astronautics, Beihang University, Beijing 100191, China*
[2]*School of Mechanical Engineering, Shanghai Jiao Tong University, Shanghai 200030, China*
[3]*Beijing Institute of Spacecraft System Engineering, Beijing 100094, China*
[4]*China Aerospace Science and Technology Corporation, Beijing 100048, China*

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Abstract This review commemorates the upcoming publication of the spacecraft dynamics and control series in China by summarizing recent progress in spacecraft dynamics and control. It highlights advancements in orbit dynamics and control, focusing on the development of convex optimization and the application of artificial intelligence in orbital optimization. It emphasizes the specialized techniques for rendezvous and docking, as well as low-thrust trajectory optimization, for improving mission efficiency. The review also discusses the evolution of attitude dynamics and control, including improvements in actuator technologies. It addresses the challenges of large-scale spacecraft, including dynamic modeling, steering strategies, and health monitoring, which are essential for ensuring operational reliability. The review further explores the theoretical progress in structural dynamics and control, focusing on the enhancement of structural control through artificial intelligence and advanced modeling techniques. It presents research on specialized structures, such as biomimetic robotics and super-large spacecraft structures. The review organizes these developments along a physics-learning integration spectrum, clarifying the complementary roles of analytical modeling, optimization, and learning-assisted decision layers. Persistent challenges in verification, scalability, and cross-domain coupling are identified, and evolutionary pathways toward system-level autonomy and constraint-consistent coordination are discussed.

Keywords spacecraft dynamics, orbit optimization, attitude control, structural dynamics, artificial intelligence

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1 Introduction

Spacecraft dynamics and control are key to the success of space missions, influencing every aspect from launch to orbit maintenance and beyond. As space missions become increasingly complex, spacecraft dynamics and control are more important than ever, demanding continuous innovation and advancement in theoretical and practical approaches.

Within the two-body, three-body, and multibody systems framework [1,2], spacecraft orbital dynamics and control have developed to emphasize control methodologies' complexity, autonomy, and intelligence. Advanced control strategies, such as convex optimization and machine learning algorithms, have been integrated to enhance the efficiency and adaptability of spacecraft in various operational scenarios [3]. The development of these methods has been further propelled by the need for novel characteristics in specialized scenarios, such as deep space exploration and on-orbit servicing, which require innovative solutions for rendezvous, docking, and formation flying under new environmental conditions.

The dynamics and control of spacecraft attitude have also seen significant progress, focusing on the unique actuation mechanisms and control performance of super-large spacecraft and micro/nano satellites. The miniaturization of satellite components and the increasing number of small satellites in orbit have driven the development of innovative control systems that are both efficient and cost-effective [4]. Concurrently, the growth in large-scale space infrastructure has led to the exploration of advanced control techniques for maintaining stability and precision in the face of complex environmental interactions.

The structural dynamics and control of spacecraft have become increasingly concerned with the multi-coupling effects introduced by super-large structures. The research challenges of large-scale space structures, such as the interaction between attitude control and structural flexibility, require high-precision multi-modal, multi-dimensional modeling and control strategies to ensure mission success. This emphasis highlights the increasing complexity of

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* Corresponding author (email: xuming@buaa.edu.cn, victory_ww@sina.com)

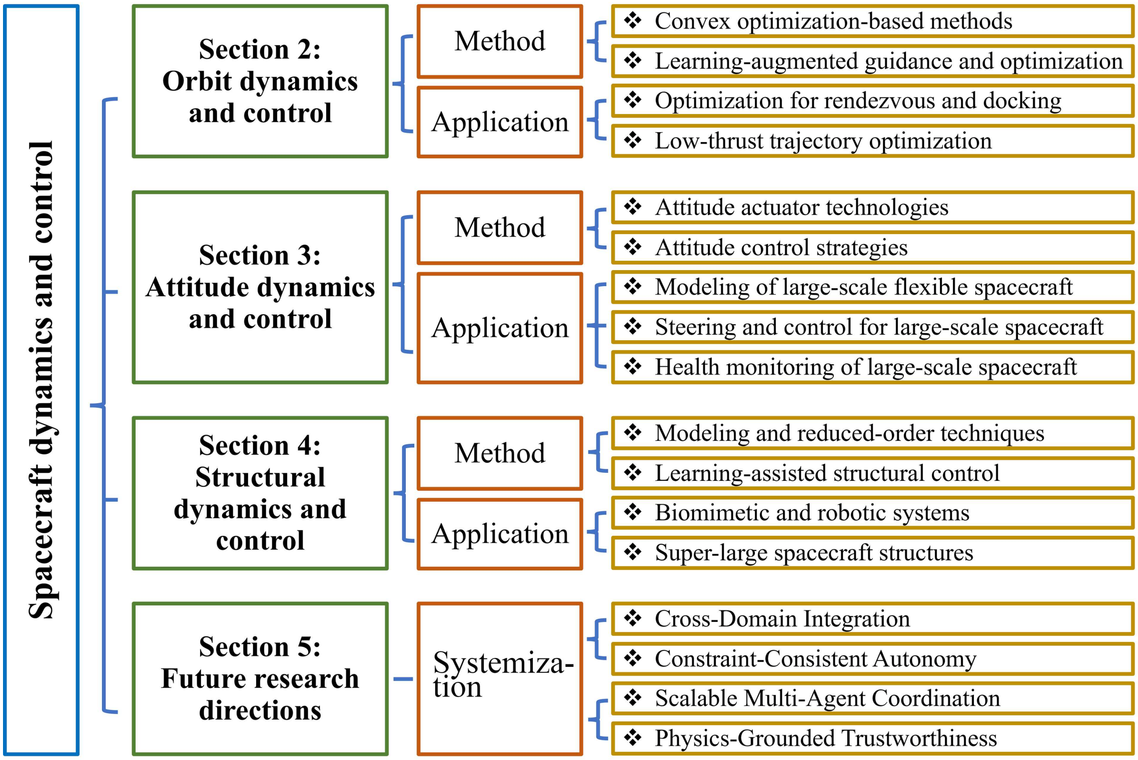

Figure 1 (Color online) Snapshot of the review structure.

the field and the corresponding need for high-precision modeling and control strategies. Furthermore, the rapid development of biomimetic space robots, with their innovative designs and control mechanisms, is pushing the boundaries of space exploration [5].

This review is motivated by the publication of the spacecraft dynamics and control series and aims to synthesize recent theoretical and technological advances in the field. Beyond documenting representative progress, the review seeks to extend the impact of the series by highlighting the complementary roles of theoretical development and engineering-oriented innovation. To this end, recent developments in spacecraft dynamics and control are organized along a physics-learning integration spectrum, rather than being framed as a dichotomy between classical and data-driven approaches. Three complementary levels are distinguished: (i) physics-preserving methods, in which analytical modeling, structure-preserving discretization, and convex optimization play a dominant role; (ii) physics-augmented learning, where learning-based modules assist model-driven solvers through tasks such as initialization, uncertainty compensation, or health monitoring; and (iii) learning-dominant decision layers, which exploit reinforcement learning or generative models to address high-dimensional or rapidly changing scenarios under supervisory constraints. This taxonomy is used consistently throughout the review to contextualize representative methods and clarify their respective roles in operational spacecraft systems. Particular attention is devoted to emerging spacecraft architectures relevant to future space missions, including space robotic systems, satellite mega-constellations, and large-scale flexible structures, in which strong coupling among dynamics, control, and system-level constraints fundamentally reshapes modeling and control requirements.

The structure of this article is organized as illustrated in Figure 1. Following the introduction, Section 2 reviews recent methodological and application-oriented advances in orbital dynamics and control, including convex optimization-based approaches, learning-augmented guidance and optimization, and their applications to rendezvous, docking, and low-thrust trajectory design. Section 3 then examines developments in attitude dynamics and control, covering actuator technologies, control strategies, and their extension to large-scale flexible spacecraft, with particular attention to modeling, coordinated control, and health monitoring. Section 4 addresses structural dynamics and control, focusing on modeling and reduced-order techniques, learning-assisted structural regulation, and emerging applications such as biomimetic robotic systems and super-large space structures. Finally, Section 5 synthesizes the overarching trends and outlines future research directions, emphasizing cross-domain integration, constraint-consistent autonomy, scalable multi-agent coordination, and physics-grounded trustworthiness as the central themes guiding the next stage of development.

2 Spacecraft orbit dynamics and control for emerging mission architectures

2.1 Methodological evolution of orbit dynamics and control

The evolution of space mission paradigms and types has catalyzed the advancement of novel mathematical methodologies and computational techniques in orbit dynamics and control. Researchers now employ analytical and numerical methods and technologies to solve spacecraft dynamical systems with higher precision, design the spacecraft trajectories under diverse environmental conditions, and assess the efficacy of orbital control strategies. In addressing the optimization of orbital rendezvous trajectories, researchers have increasingly turned to intelligent algorithms that offer enhanced flexibility and efficiency through their smart, automated, and offline solution capabilities.

2.1.1 *Convex optimization-based methods*

Convex optimization constitutes a major class of mathematical programming techniques in which both the objective function and feasible set are convex, guaranteeing a unique global optimum that can be computed efficiently using well-established polynomial-time algorithms. In contrast, spacecraft trajectory optimization is intrinsically non-convex due to the nonlinear orbital dynamics, the coupling between thrust inputs and state evolution, and mission constraints such as line-of-sight, pointing, and energy bounds. These characteristics make many practical orbital transfer problems difficult to solve directly using standard convex tools and motivate the development of convexification strategies that recast the original problem into more tractable forms. Sequential convex programming (SCP) offers a principled framework for addressing such non-convex, nonlinear, and constrained problems by constructing a sequence of convex subproblems whose solutions converge toward a locally optimal trajectory. Building on this idea, recent studies have employed lossless convexification, smooth relaxations, and successive convexification schemes to manage non-convex control constraints and terminal conditions while preserving numerical reliability [6, 7]. Moreover, hybrid approaches that integrate convex optimization with machine learning or reinforcement learning have begun to appear, leveraging convex solvers for constraint enforcement and stability while using learned components to improve initialization, cost prediction, or adaptation in complex dynamical environments.

Sequential convex programming frameworks. Sequential convex programming continuously approximates the cost and constraints of a non-convex optimal control problem through a series of convex problems, thereby solving the original problem [8, 9]. It is a novel approach applied to optimal guidance and control problems with nonlinear dynamic constraints and has been widely used in robot trajectory optimization [10], spacecraft trajectory optimization [11]. To rapidly identify local optimal solutions for spacecraft rendezvous trajectory optimization problems, Malyuta et al. [12] combined the sequential convex programming algorithm with numerical continuation, successfully generating fuel-optimal 6-degree-of-freedom (DOF) spacecraft rendezvous trajectories. Furthermore, Yang and his team [13] proposed a convexifiable minimum landing error problem, solving for the optimal asteroid landing trajectory in terms of time through sequential convex programming algorithm. In addressing low-thrust orbital optimization problems, Wang et al. [14] introduced an SCP framework that systematically converts the original nonlinear optimal control problem into a sequence of convex subproblems. Afterwards, the method proceeds through a linearize-convexify-solve-update loop: the nonlinear dynamics are locally linearized, nonconvex thrust-direction constraints are relaxed into second-order cone constraints, and a second-order cone program-based convex subproblem is solved at each iteration to update the trajectory. This iterative structure enables the algorithm to converge reliably toward a fuel-optimal low-thrust trajectory without depending on high-quality initial guesses. Building on this framework, Hofmann and Topputo [15] further improved the robustness of SCP by introducing an adaptive mechanism that responds to environmental variations rather than relying on pre-trained solution libraries.

Across these studies, SCP consistently demonstrates fast convergence and strong numerical reliability for a wide range of nonlinear orbital and landing problems. Most results report successful generation of fuel- or time-optimal trajectories, indicating that SCP is now a mature and practical tool. However, its performance still depends on careful convexification and trust-region design, and current evidence suggests that while robust, SCP may require additional safeguards for highly nonconvex environments or missions with discontinuous dynamics.

Convexification strategies for nonlinear orbital problems. When facing specific orbital optimization problems, one of the main challenges is transforming nonlinear optimization problems into convex optimization problems. This is because nonlinear problems are typically more complex, while convex optimization problems are more easily solvable. Researchers have continuously explored new methods and technologies to overcome this challenge, such as introducing new techniques and strategies, successfully converting complex non-convex problems into convex problems, and offering more feasible solutions. Malyuta et al. [16] used continuous convex optimization techniques to convert non-convex problems with mixed integer constraints into convex problems for generating fuel-optimal spacecraft rendezvous trajectories. Pinson and Lu [17] used relaxation techniques to transform nonlinear optimal control problems into relaxed problems, thereby enabling the design of optimal propellant trajectories for asteroid soft landing using convex optimization. Zhang and his team [18] linearized and discretized non-convex continuous-time optimization problems into convex discrete-time optimization sub-problems, successfully solving the 6-DOF asteroid powered-landing design problem. Furthermore, Dutta et al. [19] have addressed the fuel-optimal collision avoidance problem by combining uncertainty propagation, instantaneous collision probability calculation, and timely return of satellites to their nominal orbits through a convex treatment.

These convexification techniques generally perform well, enabling previously intractable non-convex orbital problems, such as asteroid landing, collision avoidance, and 6-DOF powered descent, to be solved efficiently with guaranteed feasibility. The reported results show clear improvements in computational robustness and solution quality. Nevertheless, most methods rely on problem-specific relaxations or linearization assumptions, suggesting that their generality and scalability still require further validation in broader mission scenarios.

Hybrid convex optimization with learning methods. Convex optimization is widely used in orbital optimization as a mathematical tool due to its efficiency and stability in handling convex problems. However, when facing actual orbital optimization problems, they often exhibit non-convex and highly non-linear characteristics, making it impossible for the convex optimization method alone to be directly applied or to find the global optimal solution. To address these limitations, recent studies have explored hybrid schemes that couple convex optimization with adaptive mesh-refinement techniques. Li et al. [20] introduced a two-layer framework in which convex optimization serves as the inner-layer solver, while multi-resolution technology (MRT) acts as an outer-layer module that adaptively adjusts grid density. The MRT evaluates local interpolation errors on dyadic grids and refines only those segments where the trajectory varies rapidly. This mechanism yields a non-uniform mesh that concentrates resolution around high-dynamics regions, reducing the global discretization size while preserving accuracy. Wang et al. [21] combined polynomial chaos (PC) theory with convex optimization technology to propose a robust trajectory optimization method for efficient generation of optimal trajectories. Benedikter et al. [22] transformed the nonlinear covariance control problem into a deterministic convex optimization problem and successfully applied optimal covariance control to low-thrust orbital optimization problems. Sarno et al. [23] simplified the orbital transfer problem into the form of a convex optimization problem and, combined with genetic algorithms, proposed a new method for autonomous reconfiguration of distributed space systems to ensure the safe guidance of spacecraft formations to the required mode, while optimizing the total propellant consumption.

Hybrid methods that integrate convex optimization with mesh refinement, uncertainty quantification, or evolutionary search show strong potential: they improve accuracy, reduce discretization cost, and enhance robustness under disturbances. Numerical evidence indicates meaningful performance gains over single-method baselines. Still, these integrated approaches remain in an exploratory stage, and their computational overhead and tuning complexity imply that more systematic assessments are needed before widespread adoption in mission-critical workflows.

2.1.2 *Learning-augmented guidance and orbital optimization*

Over the past two decades, the application of artificial intelligence (AI) in space exploration has become increasingly widespread and rapidly advancing, gaining more acceptance in the field of spacecraft control. In particular, deep learning (DL) and reinforcement learning (RL) have made significant inroads, both being subfields of AI. DL algorithms have found numerous applications in orbital optimization for maneuvering and in determining transfer costs. RL, on the other hand, has provided a multitude of solutions aimed at alleviating computational burdens. The learning-based components described below function as assistance layers rather than replacements for classical trajectory solvers. Specifically, these learning modules are typically deployed for cost estimation, initial-guess generation, or uncertainty compensation, while the enforcement of full dynamics, path constraints, and safety margins remains within model-based solvers. Offline solution libraries or maneuver datasets are used to train lightweight models that provide cost estimates or warm-start hints, while during online operation the classical solver enforces the full dynamics and all hard operational constraints such as thrust limits, pointing windows, and momentum bounds, with the learned hints helping to reduce iteration effort; when these hints become unreliable or fall outside their confidence region, the system returns to the classical solver in its nominal mode or relies on a guarded runtime-assurance scheme to preserve safety and feasibility.

Deep learning for guidance and orbital optimization. The orbital maneuvering techniques for autonomous spacecraft have progressively evolved and have been applied in many renowned space missions. Concurrently, deep learning technology has achieved significant success across various domains, capturing the attention of researchers in orbital optimization [24]. However, spacecraft navigation differs from terrestrial missions due to stringent reliability requirements and the scarcity of extensive datasets. This subsection aims to systematically investigate the current methods of autonomous spacecraft orbital maneuvering based on deep learning, focusing on acquiring key parameters for spacecraft orbital transfer and the specific applications of orbital optimization in maneuvering operations. In practice, the existing studies fall into two common roles of deep learning in orbital optimization: (a) estimating transfer-related quantities such as transfer time, fuel consumption; and (b) providing warm starts or structural guidance to classical solvers, including indirect methods, successive convexification, and model predictive control (MPC). This subsection follows this structure to highlight the core ideas and representative methods.

A first group of methods uses deep learning as a fast regression tool to estimate transfer costs, both temporal and energetic, and other key parameters that are difficult to obtain directly from conventional optimal-control formulations. Boasting formidable data-driven attributes, deep learning is capable of extracting latent patterns and correlations from a trove of historical data. These discerned patterns and relationships are then transmuted into precise assessments of transfer costs (temporal metrics and fuel expenditure) or other pivotal parameters within the purview of optimization challenges. The prognostication of transfer durations between arbitrary orbital configurations utilizing solar sails poses a formidable challenge, often necessitating the resolution of an optimal control dilemma. Inspired by the productive deployment of deep neural networks in nonlinear regression contexts, Song et al. [25] have leveraged deep learning to estimate the transfer durations for solar sail trajectories among proximate celestial bodies. Li et al. [26] have adeptly applied deep feedforward neural networks to predict three optimal paradigms: the temporal metrics for time-optimal low-thrust transfers, the energetic considerations for fuel-optimal low-thrust maneuvers, and the fuel consumption. Xie et al. [27] introduced an online framework for training deep neural networks (DNN) tailored to optimize low-thrust trajectories rapidly. This framework's online characteristic lies in its capacity to iteratively refine the trained DNN with novel low-thrust transfer data emanating from newly identified asteroids, thereby circumventing the exigencies for repetitive and onerous retraining endeavors. This framework is particularly productive in operational contexts where novel data are acquired on a scheduled basis, surpassing sequential network architectures regarding generalizability and scalability.

A second group of studies employs deep learning to generate warm starts or structural guidance for classical optimal-control solvers, thereby improving convergence reliability and reducing iterative computational burden. Trajectory optimization problems in orbital maneuvering are typically addressed through the resolution of constrained optimal control problems (OCPs). Compared to conventional indirect and direct approaches, deep learning significantly reduces computational costs, enhances solution efficiency, and increases the likelihood of identifying global optimal solutions. Deep learning models can extract high-dimensional nonlinear patterns from historical maneuver data and thereby enhance the accuracy of trajectory optimization. A typical three-phase deep neural network architecture integrates multiple specialized subnetworks, an Earth-shadow prediction module, a transfer-time forecasting network, and two costate-prediction networks for illuminated and shadowed conditions [28]. By jointly processing mission parameters through these interconnected components, the framework produces refined initial costates and timing estimates, offering a more reliable foundation for optimal orbital station-keeping. Cheng et al. [29] have introduced a real-time optimal control approach that harnesses deep learning technology to ascertain the minimum-time trajectory for solar sail spacecraft engaged in orbital transfer missions. An indirect method is utilized to tackle the two-dimensional orbital transfer problem aimed at minimizing time, incorporating co-state normalization techniques to elevate the probability of discovering the optimal solution. By leveraging deep learning technology, offline training based on the derived optimal solutions enables the real-time generation of guidance commands during flight, thereby overcoming the longstanding challenge of trajectory generation. Building on this foundation, an interactive network training strategy has been proposed, which enhances the probability of successfully identifying the optimal method by providing a promising initial guess for the indirect approach. Moreover, a multi-scale network collaboration strategy has been devised to rectify the recognition deficiencies of DNN with diminutive input values, facilitating high-precision control over terminal orbit insertion. The conjecture of an initial solution significantly influences the convergence of the indirect method, particularly in the context of continuous low-thrust orbital optimization problems. Yin et al. [30] have proposed an intelligent initial solution provision method predicated on DNN to expedite the generation of optimal trajectories for low-thrust orbital transfers, taking into account energy-optimal trajectories and fuel-optimal trajectories under three distinct terminal conditions. Furthermore, Yang et al. [31] have introduced a trajectory optimization method based on data-free DNN for the interception of non-cooperative maneuvering spacecraft. The problem is articulated as a standard constrained optimization problem by employing differential game theory and the minimax principle. A novel DNN has been engineered to integrate the interception dynamics model into the network, allowing it to participate in the gradient descent process, thereby endowing the network with an understanding of physical constraints and diminishing the learning burden on the network. Recently, generative modeling techniques have also been explored to address optimal control problems with complex constraints. For instance, physics-aware diffusion mapping has been proposed to reconstruct admissible solution manifolds for spacecraft co-location optimal control problems, enabling efficient generation of feasible control trajectories while preserving orbital dynamic consistency [32].

Overall, existing deep-learning-based orbital optimization methods show clear benefits in reducing computation time and producing fast estimates or warm starts, and most studies report favorable agreement with classical optimal-control solutions. However, their performance remains sensitive to training data coverage and generalization across dynamical regimes, indicating that these approaches while promising are not yet fully mature for safety-critical, on-board autonomy. Current evidence suggests that deep learning serves best as an assistive module—most effectively in cost estimation, warm-start generation, and uncertainty-aware refinement—rather than as a standalone decision mechanism in safety-critical orbital operations.

Reinforcement learning for decision-aware orbital optimization. Traditional optimization techniques, such as the indirect and direct methods, offer theoretically precise solutions but are often impractical for spacecraft orbital optimization due to excessive computational costs. These methods demand numerous iterative processes and intricate numerical analyses, consuming significant computational resources and potentially leading to slow solution processes or even an inability to find feasible solutions within a limited timeframe in practical applications. To surmount these limitations, researchers have explored novel approaches that integrate traditional optimal control techniques with reinforcement learning methods. Reinforcement learning, a branch of machine learning, learns optimal policies through interaction with the environment [33]. Reinforcement learning offers a complementary framework for addressing high-dimensional and sequential decision problems in orbital optimization, particularly when computational efficiency and adaptive policy generation are required.

During the complex decision-making process of spacecraft orbital maneuvers, each action selection is predicated on an accurate analysis of the current state. While past decisions and actions shape the present system state through orbital dynamics, practical maneuver planning places primary emphasis on current flight conditions and mission requirements when determining subsequent actions. This state-dependent decision-making paradigm closely mirrors recent developments in autonomous robotic systems, where resilient and replanning-oriented frameworks have demonstrated impactful advances in embedding state-aware replanning and disturbance-tolerant decision logic into real-time, constraint-sensitive autonomy [34, 35].

Motivated by this perspective, reinforcement-learning-based formulations have been increasingly explored in spacecraft orbital optimization as a means of augmenting classical physics-based solvers with adaptive decision capability. Arora and Dutta [36] investigated the electric orbit-raising problem by decomposing it into a sequence of coupled optimization subproblems and showed that adaptive modulation of objective-function weights plays a critical role in shaping low-thrust ascent efficiency. By embedding the weight-selection process within a reinforcement-learning framework, their work illustrates how learning mechanisms can regulate optimization structure online while preserving the underlying orbital-dynamics formulation.

Building on this structured, state-dependent learning paradigm, Holt et al. [37] incorporated an actor-critic architecture into the Lyapunov-based Q-law, yielding a control policy whose parameters evolve explicitly with the system state. Notably, the availability of analytical Jacobian information allows learning-driven adaptation to coexist with stability-oriented design principles, distinguishing this approach from black-box optimization schemes. Numerical investigations of geosynchronous transfer orbit (GTO)-geostationary Earth orbit (GEO) and low Earth orbit (LEO)-GEO transfers further demonstrated robustness against navigation errors and thruster misalignments, highlighting the potential of such formulations for onboard autonomous orbit-raising and orbital reconfiguration.

Along similar lines, Zaidi et al. [38] proposed a reinforcement-learning-based framework for computing geostationary transfer orbits and beyond-GTO low-thrust transfers using a cascaded soft actor-critic (SAC) architecture. In this work, physically informed reward shaping, through gradient-assisted terms derived from orbital elements, is used to enforce mission-level constraints, enabling efficient convergence while maintaining sensitivity to orbital dynamics. Together, these studies reflect a broader trend toward reinforcement-learning approaches in space applications that inherit the state-aware replanning philosophy demonstrated in earlier autonomous robotics research, while remaining grounded in physically meaningful structure and control requirements.

Interplanetary low-thrust orbits are characterized by long thrust periods, often in unknown environments, making spacecraft guidance and navigation problems more challenging for traditional optimal control methods. Traditional optimization methods are computationally expensive and prone to getting stuck in local minima. Reinforcement learning provides a viable alternative for the robust design of interplanetary trajectories. Miller et al. [39] demonstrated a reinforcement learning technique for devising complex decision policies to plan interplanetary transfers. Proximal policy optimization (PPO) was used, considering a fixed-length reference trajectory from Earth to Mars, sampled into a finite number of states, training to produce a closed-loop controller capable of transferring between Earth and Mars. Zavoli et al. [40] investigated the robust design of low-thrust interplanetary trajectories under severe dynamical uncertainties. To embed robustness within learning-based guidance, the stochastic optimal control problem was reformulated as a time-discrete Markov decision process, enabling compatibility with modern reinforcement-learning frameworks. The resulting advantage actor-critic architecture maps spacecraft states

Table 1 Representative PPO/SAC variants and their characteristics in spacecraft orbit-optimization tasks.

Algorithm/variant	Core mechanism	Strengths for orbit optimization	Limitations/ considerations
PPO [41]	Clipped surrogate objective; stable policy updates	Reliable convergence with limited data; robust under step-size variability; suitable for sequential low-thrust maneuvering	Limited exploration in highly multimodal landscapes
MR-PPO (multi-reward PPO) [43]	Multi-objective reward shaping	Captures fuel consumption-time-feasibility trade-offs; supports multi-arc transfer design	Requires careful reward balancing
TR-PPO (trust-region PPO) [44]	Stricter update bounds	Predictable convergence under high-fidelity dynamics	Reduced exploration capability
SAC [42]	Entropy-regularized actor-critic framework	Strong performance in continuous-thrust tasks; good global search capability; handles multimodal disturbances	Higher computational cost; slower convergence
TD3-SAC hybrid [45]	Dual-critic reduction of overestimation bias	Effective for large continuous-action spaces and long-arc maneuvering	Increased architectural complexity
Attention actor-critic [46]	Self-attention for long-horizon dependency capture	Learns structured thrust arcs; suitable for extended low-thrust transfers	Higher inference cost; requires pruning for onboard use

to thrust actions through an actor network, while a critic network evaluates the value of each state-action pair to refine the policy. The environment propagates the spacecraft dynamics, computes the corresponding reward, and returns the updated state to close the decision loop. Leveraging an open-source policy-optimization algorithm, the trained network yields a robust nominal trajectory together with closed-loop guidance laws that compensate for uncertainties. Numerical experiments for an Earth-Mars transfer further demonstrate the effectiveness of the learned policy.

As summarized in Table 1, PPO-type algorithms [41] offer stable and predictable convergence even under limited data and variable step sizes, making them well suited for sequential low-thrust maneuver planning. SAC [42], in contrast, leverages entropy-regularized exploration and therefore excels in continuous-thrust settings, multimodal disturbance environments, and large continuous action spaces, albeit at higher computational cost. Building upon these baselines, multi-reward PPO [43] improves multi-objective transfer performance, trust-region PPO [44] enhances robustness under high-fidelity orbital dynamics, twin delayed deep deterministic policy gradient (TD3)-SAC [45] hybrids mitigate overestimation issues for long-arc maneuvers, and attention-augmented actor-critic architectures [46] capture long-horizon thrust dependencies that arise in extended low-thrust transfers. Overall, PPO-family methods remain advantageous when data and computation are constrained, whereas SAC-type and attention-based variants can achieve superior asymptotic performance when richer exploration and long-term structure learning are required.

A practical rule of thumb can be drawn from the above RL-based methods. RL or hybrid RL with classical optimization is most suitable when the spacecraft operates in high dimensional or rapidly changing state spaces and when frequent re-planning is required, which often occurs in proximity operations, pursuit and evasion scenarios, and real-time collision avoidance. Classical optimal control and model predictive control remain preferable when hard constraints and verifiability requirements dominate, since thrust limits, pointing windows, angular momentum bounds, and strict terminal conditions must be satisfied with reliable guarantees; in such cases, RL is best used as a supporting module that provides warm starts or local corrective guidance. When onboard computational resources are limited or when the guidance cycle is short, lightweight models with explicit constraint structures are generally favored because they offer predictable execution time and reduce verification and validation burden. These considerations turn the preceding case-based survey into concrete guidance for choosing appropriate maneuver-planning strategies in practice.

Across the literature, reinforcement learning methods successfully generate feasible transfer policies and demonstrate strong potential for long-horizon decision-making under uncertainty, especially for low-thrust and interplanetary missions. Yet, their substantial training cost, sensitivity to reward shaping, and the absence of formal stability or constraint-satisfaction guarantees limit their immediate suitability for safety-critical onboard deployment. Current reinforcement-learning formulations are therefore better interpreted as decision-support or adaptive replanning layers that complement, rather than replace, certified optimal-control pipelines.

2.2 Orbit optimization for mission-oriented and non-cooperative scenarios

As aerospace technology advances, spacecraft's orbital dynamics and control progress towards greater precision and autonomy. Traditional orbital control methods primarily relied on directives and controls from ground control centers. In contrast, now, more spacecraft are equipped with autonomous decision-making and control capability. They can adjust their orbits independently based on environmental changes and mission requirements, achieving more flexible and efficient operations. The dynamics and control of spacecraft orbits are also actively applied in multi-domain cooperative and exploration missions. For instance, through precise orbital control, Earth observation satellites can accomplish high-resolution observation and monitoring, providing vital data support for fields such as environmental protection and climate change. Concurrently, the dynamics and control of spacecraft orbits play a significant role in deep space exploration, such as planetary exploration and the operation of the International Space Station, offering a technological foundation for humanity's cosmos exploration. The mathematical models of spacecraft dynamics are crucial in the process of realizing spacecraft control. Traditional dynamical equations are mainly based on the principles of Newtonian mechanics. However, as research into spacecraft motion delves deeper, the effects of various other influencing factors have been discovered, such as gravitational assists, atmospheric drag, solar radiation pressure, and non-spherical gravitational effects; simultaneously, in conjunction with mission requirements and according to the complexity of space missions, the dynamical equations describing spacecraft are established by integrating the corresponding physical models and mathematical tools.

2.2.1 *Orbit optimization for rendezvous and docking*

The rendezvous and docking mission of spacecraft is an exquisite space operation and an integral component of space missions. It encompasses launch, orbital maneuvering, target approach, capture, physical docking, mission execution, separation, and subsequent return or continuation of the mission. This process demands a high degree of automated control, precise navigation, and stringent safety checks to ensure successful mission execution, which is of significant importance for fields such as active space debris removal, on-orbit servicing, and maintenance, on-orbit assembly of large space structures, human-crewed spaceflight, asteroid exploration, and deep space exploration. Orbital optimization during the rendezvous and docking process is a complex issue considering fuel efficiency, time efficiency, safety, stability, fault tolerance, multi-objective optimization, dynamic programming, constraint conditions, real-time adjustments, and cost-effectiveness. It requires designers to employ advanced mathematical models and computer simulation technologies to identify the optimal or near-optimal path that minimizes while ensuring the safety distance and relative velocity of the spacecraft throughout the entire rendezvous and docking process under constraints such as the physical dimensions of the spacecraft, propulsion system capabilities, and flight envelopes. Additionally, designers must consider potential errors and anomalies and orbital adjustments based on real-time data during actual flight operations to address unpredictable external factors and ensure that the entire rendezvous and docking process is efficient and safe. Bang et al. [47,48] proposed an optimal multi-target rendezvous problem based on multiple chaser spacecraft for active debris removal (ADR) missions. He presented the dynamical equations for the optimal multi-target Lambert rendezvous in active debris removal missions and provided multi-target rendezvous strategies for multiple spacecraft conducting active debris removal. A two-stage framework was proposed to solve the presented multi-target rendezvous problem. This framework reduces the complexity of the problem by decomposing it into two different types of optimizations (trajectory optimization and combination optimization) and effectively obtains its solution. Li et al. [49] regarded the multi-debris removal problem as similar to the multi-asteroid rendezvous problem and proposed a rapid and effective dynamical equation for low-thrust J2 perturbed multi-debris removal. The selection of the optimal rendezvous sequence is a global optimization problem, which is solved using beam search with variable beam width and parallel processing technology. An indirect method using equal division units is employed to solve the J2 perturbed fuel-optimal low-thrust problem. Huang et al. [50] addressed the global optimization of multi-target continuous rendezvous trajectories by decomposing the task into three coordinated sub-problems. Huang et al.'s framework first assigns targets to each orbital transfer vehicle via RAAN-drift-based cost evaluation and a dynamically guided genetic algorithm. The second step determines the visiting order and rendezvous times using mixed-integer optimization supported by a Δv interpolation grid. The third step refines each leg through multi-impulse trajectory optimization. To efficiently couple these layers, Huang et al. further introduced a dual dynamic programming strategy that leverages periodicity features in rendezvous dynamics, enabling fast global search over feasible rendezvous periods.

Spacecraft rendezvous and docking are complex and sophisticated engineering fields with significant advancements in recent years. Several scientists have used the Clohessy-Wiltshire-Hill (CWH) equations as a foundation and developed their respective dynamic models for different orbital environments and mission requirements. These studies have collectively advanced the technology of spacecraft rendezvous and docking, especially in dynamic modeling and control algorithms, demonstrating the remarkable progress in the field. Jewison et al. [51] proposed the relative dynamic equations between the chasing and target spacecraft in the on-orbit assembly mission of the geostationary orbit and the discrete version of the dynamic equations over time. Gurfil [52], based on the CWH relative motion equation, proposed a dynamic model for the rendezvous and docking of electric propulsion spacecraft with constant thrust magnitude constraints and eccentricity effects. The core of these scientific issues lies in accurately simulating and optimizing spacecraft's rendezvous and docking process under different orbital conditions and improving the efficiency and accuracy of rendezvous and docking through mathematical modeling and algorithm design. Driven by science, planetary exploration, and resource development engines, the related technologies of rendezvous and docking have also been applied in small celestial body exploration, leading to a surge in research, including asteroids and comets. Due to the long communication delays near asteroids and the complex dynamic environment [53], asteroid exploration missions are more challenging because there is limited information about the gravity and environment of asteroids. If celestial bodies and their orbital environments are uncertain, then all plans made on the ground for implementation in space may fail greatly. Wang et al. [54] considered the interplanetary orbit transfer problem and proposed a power-limited asteroid rendezvous dynamic model. An effective indirect method was developed using the analytical multiplier associated with the scalar interior point constraint, establishing a computational framework for solving time and fuel-optimal problems. The result is an algorithm with an exact bang-bang solution and gradient, a wider convergence domain, and high computational efficiency. Multi-asteroid exploration using low-thrust propulsion requires the design of transfer trajectories, the selection of visit sequences, and the estimation of propellant budgets. Fan and colleagues [55] combined finite Fourier series (FFS) with Monte Carlo tree search (MCTS) to efficiently design multi-asteroid exploration trajectories. The FFS method rapidly provides transfer-trajectory approximations that serve as accurate initial guesses for subsequent optimization. MCTS explores asteroid-visit sequences through a layered tree structure in which each node corresponds to a candidate target and the cumulative ΔV acts as the performance index guiding the search. Qi et al. [56] proposed a fast MCTS pruning algorithm to quickly complete asteroid sequence selection and trajectory generation for multi-spacecraft exploring multiple asteroids. Combined with the Bezier shape-based (SB) method and MCTS, it rapidly searched exploration sequences and efficiently optimized continuous transfer trajectories. Under the same conditions, the Bezier SB method obtained transfer trajectories with better performance indicators faster than the finite Fourier series SB method.

Overall, current rendezvous and docking optimization methods ranging from multi-target debris-removal planning to asteroid-rendezvous design demonstrate strong practical effectiveness, with most studies reporting feasible, fuel-efficient, and computationally tractable trajectories. Nevertheless, the majority of existing formulations rely on problem-specific decompositions, heuristic sequencing, or simplified environmental models. Their scalability to large target sets, sensitivity to modeling uncertainty in weak-gravity fields, and integration with onboard constraint-verification architectures remain open challenges that must be addressed before routine autonomous deployment.

2.2.2 *Low-thrust trajectory optimization*

Since 2012, the development of electric propulsion and even all-electric propulsion technology has been vigorous, and the development and iteration of electric propulsion satellite platforms have been rapid, making the study of low-thrust orbital optimization technology a hot topic internationally. Low-thrust orbital optimization evolves into a control problem of non-smooth and discontinuous systems, depending on whether the engine provides continuous thrust, whether the thrust amplitude is time-varying and limited, and whether the thrust direction angle is continuously adjustable, with extreme system complexity and non-linearity. On the other hand, the long transfer time and multiple transfer orbits caused by low thrust also make the solution and convergence of low-thrust optimization problems extremely difficult.

The low-thrust orbit transfer problem is a multi-phase optimal control problem in which the spacecraft can only thrust during the phase when it has a line of sight to the sun. Event constraints based on the geometric shape of the penumbral shadow area are enforced between phases to determine the time spent in the eclipse. Graham and Rao [57] developed an initial guess generation method by solving a series of single-phase optimal control problems and analyzing the resulting trajectories to roughly determine the spacecraft's entry and exit positions of the Earth's shadow, thereby constructing a useful guess. Sreesawet and Dutta [58] proposed an optimization framework based on a direct method, using the pseudospectral method for trajectory optimization. This method transforms the continuous-time optimal control problem into a static nonlinear programming problem (NLP) and then uses a nonlinear programming solver to solve it. In addition, a Lyapunov-based initial guess generation scheme was introduced to facilitate the rapid generation of initial solutions for the optimization problem. Jiang et al. [59] proposed a shape method based on Bezier curves for rapid costate estimation, using Bezier curves to define the shape of the trajectory and then optimizing these shape parameters through adjoint estimation to obtain a better trajectory. This method is used for the optimization of indirect low-thrust transfer trajectories. The introduction of this method is to address some of the challenges in low-thrust trajectory optimization, such as strong nonlinearity, numerical sensitivity, and the lack of physical significance in the initial guess of the accompanying state. Huang et al. [60] reformulated the low-thrust perturbed-orbit rendezvous problem by prescribing a quasi-optimal thrust-switch strategy that converts the original sensitive multi-revolution transfer into a low-dimensional parameter optimization. The near-optimal trajectory is partitioned into three phases–thrusting to an intermediate drift orbit, natural drifting with thrust off, and a final thrusting arc to the target orbit thus capturing the essential structure of the optimal solution while greatly reducing computational complexity. The resulting few-parameter model is solved using differential evolution, followed by a lightweight analytical correction to remove accumulated numerical errors.

Beyond phase decomposition and thrust-switch strategies, recent studies have further explored the intrinsic structure of low-thrust optimal control problems from the perspectives of solution space topology, homotopy continuation, and dynamical reachability. By combining energy-based and control-structure-preserving homotopies, a systematic solution-space exploration framework was developed for low-thrust minimum-time transfer problems, enabling robust convergence across multiple local optima and improving the reliability of indirect and hybrid solution methods [61]. Building on this perspective, homotopic smoothing techniques were introduced to regularize non-smooth optimal control problems with power and thrust constraints, transforming discontinuous low-thrust dynamics into a sequence of smooth auxiliary problems that can be efficiently solved using gradient-based methods [62]. In parallel, the reachable set of low-thrust spacecraft was characterized in a reduced-order setting, providing quantitative insight into maneuverability limits and control authority under severe thrust constraints [63]. These methodological advances have also been applied to practical geosynchronous mission scenarios. By explicitly exploiting resonant and inclined dynamical structures in the geosynchronous region, low-thrust station-keeping strategies were formulated to significantly reduce long-term control effort while maintaining orbital performance [64, 65]. Together, these studies demonstrate how physics-informed homotopy design, reachability analysis, and dynamical structure exploitation can jointly enhance both the theoretical tractability and practical efficiency of low-thrust trajectory optimization.

Across the literature, low-thrust trajectory optimization methods have proven effective at generating feasible multi-revolution transfers and improving convergence in highly nonlinear settings, particularly when enhanced by advanced initial-guess strategies or reduced-parameter reformulations. Most results show good accuracy relative to indirect or high-fidelity benchmarks, demonstrating that the field has achieved a high degree of numerical maturity. However, convergence behavior remains sensitive to shadow-transition discontinuities, multi-revolution coupling, and initial-value conditioning in highly nonlinear regimes. Ensuring reliable convergence under operational disturbances and limited onboard computational resources continues to be a critical step toward flight-qualified low-thrust autonomy.

3 Spacecraft attitude dynamics and control under coupled and scalable systems

3.1 Methodological evolution of attitude dynamics and control

Attitude dynamics and control are fundamental issues in spacecraft technology, with a long history and rich research outcomes. The attitude dynamic model has achieved fruitful results and can address most problems. For the classical attitude description of rigid spacecraft, the Newton-Euler method, coupled with tools such as Euler angles and quaternions for modeling, yields satisfactory results [66, 67]. For the integrated attitude and orbit modeling, acceptable results can be achieved using dual quaternions and Lie group algebra [68, 69].

With the foundational attitude representations well established, recent work has increasingly moved toward the design of attitude actuation systems and control architectures. This transition is strongly shaped by two markedly different classes of spacecraft missions. The first class involves miniaturized platforms deployed in large constellations [70]. Starlink is a representative example: by the end of 2023, more than 5500 spacecraft—typically around 270 kg each—had been placed in orbit. These satellites operate under stringent mass, power, and cost constraints. Research teams analyzing Starlink operations, such as Yang and Soloviev [71], have highlighted that compact reaction-wheel assemblies, simple torque-rod auxiliaries, and highly autonomous control logic are essential for supporting high-tempo orbit-raising, collision-avoidance maneuvers, and continuous broadband pointing across thousands of low-cost units. The second class comprises high-capability spacecraft designed for deep-space and high-orbit missions. The Chang'e-5 spacecraft, with a launch mass of about 8.2 tons, required precise multi-axis pointing, coordinated attitude-orbit coupling, large-angle reorientation maneuvers, and fault-resilient operation throughout its lunar sampling and return mission. Research teams involved in Chang'e-5, including Liu, Li, and Zhang [72], report the use of high-precision gimbaled actuators, large inertia wheels, multi-sensor fusion, and multi-loop control structures capable of meeting tight pointing requirements and handling thermal-mechanical disturbances.

3.1.1 *Attitude actuator technologies and disturbance characteristics*

The primary actuators for satellite attitude control include reaction wheels (RWs), control moment gyroscopes (CMGs), and magnetorquers. Both RWs and CMGs utilize angular momentum to regulate the satellite's orientation. RWs are commonly employed for attitude control in small to medium-sized satellites, whereas CMGs are typically used for larger satellites [73]. Magnetorquers leverage the Earth's magnetic field to generate torque for attitude control, commonly used in the attitude control of LEO small satellites [74].

A representative high-performance small-spacecraft example is NASA's ASTERIA CubeSat, which remains a widely referenced benchmark for precision attitude control on 6U-class platforms. ASTERIA employed a three-wheel reaction-wheel assembly in the millinewton-meter regime (peak torque around 15 mN·m, momentum storage around 15 mN·m·s) together with low-power magnetorquers for momentum unloading. In orbit, the spacecraft achieved 0.5–2 arcsec fine-pointing accuracy and sub-arcsecond stability over observation intervals of tens of minutes [75]. These results demonstrate that miniaturized actuators, when coupled with high-accuracy sensors and tightly integrated estimation-control loops, can deliver photometry- and communication-grade pointing performance on mass- and power-limited platforms, and they provide a concrete reference envelope for actuator sizing, disturbance-management policies, and controller co-design in small-satellite missions [76–79].

On the large-spacecraft side, ESA's Euclid mission (launched in 2023) offers a recent benchmark for high-precision actuation and closed-loop stability. Euclid employs reaction-wheel assemblies delivering approximately 75 mN·m of peak torque and about 4 N·m·s of momentum-storage capability per wheel, complemented by cold-gas micro-propulsion thrusters for fine attitude trimming. Its attitude-control system is required to maintain pointing stability in the tens-of-milliarcsecond range—specifically, a 75 mas (3σ) stability requirement during typical science exposures [80]. This level of performance illustrates the actuator authority and disturbance-rejection capability necessary for wide-field cosmology observations and provides actionable guidance for the design of future large platforms, including required torque margins, momentum-management budgets, micro-thruster trimming bandwidth, and the controller stability needed to sustain long-duration scientific operations [81].

Concurrently, the need to improve actuator robustness has motivated a class of control-oriented approaches that explicitly address the recognition, separation, and compensation of composite disturbances entering the attitude-control loop. These disturbances typically arise from actuator-induced uncertainties, flexible-structure couplings, and other parasitic excitation effects that are difficult to isolate using conventional modeling assumptions. To this end, an input-excitation disturbance separator has been proposed and successfully applied to spacecraft attitude-control systems, providing a powerful and structurally insightful tool for disentangling actuator-induced uncertainties from flexible-structure-related disturbances and other coupled excitation effects [82]. In parallel with such model-based disturbance separation strategies, recent studies have explored signal-processing- and data-driven pipelines for actuator condition monitoring and fault identification. Representative frameworks employ time-frequency analysis combined with deep-learning architectures, such as the Short-Time Fourier Transform-CNN workflow, to transform vibration or current signals into discriminative time-frequency representations and classify emerging fault modes under nonstationary operating conditions. These approaches enable early detection of imbalance, bearing degradation, and related failure mechanisms, thereby supporting the development of reliable health-monitoring and predictive-maintenance capabilities for momentum wheels and control moment gyroscopes [83–87].

Overall, recent flight missions from compact CubeSats like ASTERIA to large observatories such as ESA's Euclid demonstrate that modern actuator suites can reliably deliver arcsecond- to milliarcsecond-level pointing performance when paired with high-quality sensing and closed-loop estimation. These results indicate a high level of technological maturity, especially for reaction wheels and CMGs in nominal regimes. However, actuator degradation and fault modes remain a limiting factor, and emerging data-driven health-monitoring approaches, while promising, are still developing toward the reliability required for long-duration autonomous operations.

3.1.2 *Attitude control strategies under uncertainty and coupling*

Satellite attitude control methods for small and large spacecraft demand high precision and efficiency. Moreover, the control system is subject to various engineering constraints and uncertainties in real-world scenarios, which may lead to imperfect execution or deviations in the control laws [88]. During the control process, engineering constraints are often introduced by the attitude control actuators of spacecraft, such as actuator saturation, actuator failure, and sensor malfunctions [89]. Uncertainties are primarily attributed to the spacecraft components and the space environment, including uncertainties in spacecraft inertia and torque. Research on attitude control algorithms focuses on achieving high control performance considering multiple constraints or uncertainties.

There are two main research directions for control algorithms under constraints and uncertainties. One direction is to design highly robust and adaptable control strategies that can converge under various constraints and disturbances. The commonly used foundational algorithms in this direction are sliding mode control [90], adaptive control [91], and fault-tolerant control [92]. Scholars have combined fundamental control algorithms, employing adaptive parameters and variable structure techniques to achieve high-quality control under various engineering constraints and multiple disturbances [93–96]. In a parallel line of research, considerable effort has been devoted to modeling and compensating system uncertainties so that the control law remains effective under perturbations. Representative approaches, such as the finite-time prescribed-performance learning-based controller, approximate unknown dynamics or external disturbances in real-time and inject adaptive compensation into the control loop. These methods enable the controller to maintain tracking accuracy under parameter variations, unmodeled dynamics, and nonstationary disturbances. Filtering-based estimators, adaptive update laws, and learning-based approximators have all been employed to refine the control input and enhance robustness against uncertainty [97–101].

Across the literature, advanced attitude-control strategies, whether based on robust control, adaptive compensation, or learning-augmented uncertainty modeling, have consistently shown strong performance in maintaining tracking accuracy under actuator constraints and environmental perturbations. Simulation results generally confirm their effectiveness, but most methods still lack large-scale flight validation, and their robustness guarantees remain partly dependent on modeling assumptions. Consequently, these algorithms demonstrate clear potential yet requires further maturation before they can fully meet the demands of safety-critical, long-duration space missions.

3.2 Dynamics and control challenges for large and super-large spacecraft

Spacecraft attitude dynamics and control exhibit clear scale-dependent characteristics, and the transition from small to large and ultimately to super-large platforms fundamentally reshapes the dominant rotational behavior and the associated control challenges. Small spacecraft operate primarily in a near-rigid-body regime, where disturbance torques are often comparable to the available actuation and flexible effects arise only in a few low-order appendage modes. Their control performance is therefore strongly tied to disturbance estimation accuracy, actuator authority, and limited sensing resources. Large spacecraft, by contrast, display pronounced rigid-flexible coupling: attitude maneuvers readily excite low-frequency structural modes, thermal-elastic drift accumulates over long durations, and high-value or precision payloads impose milliarcsecond-level pointing-stability requirements. In this class, mode-aware modeling, vibration suppression, disturbance reconstruction, and certifiable control architectures become essential to ensure performance and robustness. Super-large spacecraft refer to space systems whose physical dimensions and structural flexibility are sufficiently large that conventional rigid-body assumptions and low-order flexible modeling become inadequate. Such platforms operate in a regime where structural deformation modifies the effective inertia, elastic waves propagate across distributed, lightly damped structures, and attitude motion couples strongly with structural dynamics. As a result, super-large spacecraft must contend with distributed sensing, asynchronous actuation, and gradual on-orbit performance variations, requiring explicit consideration of structure-attitude coupling, distributed dynamics, and vibration effects in both modeling and control. The scale-dependent dynamics summarized above motivate different levels of modeling fidelity, estimator structure, and control strategy across platforms. Subsection 3.2 reviews these challenges and discusses recent advances in cross-scale attitude modeling, flexible-mode management, and robust stabilization for increasingly complex spacecraft architectures.

3.2.1 *Dynamic modeling of large-scale flexible spacecraft*

Utilizing an accurate super-large spacecraft dynamics model to simulate actual motion is the most effective way to address structural vibrations and structure-attitude-orbit coupling. Consequently, scholars have conducted extensive research in this direction. Unlike classical spacecraft, super-large spacecraft have numerous flexible attachments, and low-frequency vibrations between structures need to be considered in dynamic modeling. Therefore, scholars have focused on the dynamic characteristics of flexible attachments and large deformations, researching efficient computational models [102–105]. Based on Euler-Bernoulli beam theory and Hamilton's principle, Fu et al. introduced non-Cartesian deformation variables. They proposed a nonlinear dynamic model for super-large spacecraft with ultra-flexible deployable structures [106]. Han et al. utilized the dynamic stiffness method for dynamic modeling of spacecraft at a scale of several kilometers, achieving results consistent with finite element solutions [107]. The flexible dynamics model of super-large spacecraft can be articulated through the research on modeling techniques. However, vibrations induced by liquid sloshing can impact the model's accuracy, necessitating further consideration. To cope with the attitude-disturbance coupling introduced by liquid sloshing, recent studies have combined geometric modeling and intelligent approximation methods to characterize sloshing-induced moments [108, 109]. The representative adaptive control framework in [108] integrates tracking-error kinematics, disturbance observation, neural-network-based uncertainty compensation, and multi-stage filtered torque generation to counteract the slosh-induced disturbances. This structured architecture enables the controller to estimate, filter, and reject the time-varying sloshing effects in real-time, thereby enhancing the robustness of liquid-filled spacecraft attitude tracking. Additionally, they have designed attitude and orbit control systems to suppress angular velocity oscillations of spacecraft, thereby preventing additional vibrations in super-large spacecraft [110]. However, the problem of liquid sloshing and the modeling of super-large spacecraft are considered separately. When liquid sloshing is integrated into the model, further research and observation are required to determine whether the vibrations can be effectively suppressed.

Recent modeling efforts have successfully captured key flexible-rigid coupling effects and reproduced low-frequency structural behaviors with good agreement against high-fidelity simulations, indicating that current dynamic models can effectively support preliminary analysis and controller design. However, liquid sloshing, large deformations, and multi-field coupling are still treated in isolation, and integrated validation remains limited. As a result, while existing methods perform well in controlled studies, additional work is required before fully unified structure-attitude-orbit-slosh models can achieve mission-ready maturity [111].

3.2.2 *Steering and control strategies for large-scale spacecraft*

The primary cause of structural vibration and structure-attitude-orbit coupling issues in super-large spacecraft stems from the vibrations generated by the actuators, which propagate at low frequencies through the structures. Scholars have explored novel actuation methods that minimize vibration and design innovative structures with poor vibration transmission characteristics. These efforts aim to mitigate both structural vibration and the extent of structure-attitude-orbit coupling. Traditional actuators generate control torques through angular momentum exchange, inevitably leading to vibrations. Consequently, researchers utilize novel actuation devices such as thin-film reflectivity control mechanisms to control torques [112–114]. While these new devices boast the advantage of being vibration-free, their drawbacks are also apparent: they generate relatively small torques and are highly susceptible to environmental influences. Therefore, their application is limited to select super-large spacecraft with low attitude control requirements and stable operating environments. Super-large spacecraft, characterized by significant mass and interconnected structure, pose challenges in suppressing the propagation of low-frequency vibrations. Scholars attempt to mitigate these issues through innovative structural designs, which aim to reduce spacecraft mass and enhance vibration isolation. Regarding mass reduction, Boone et al. reimagined the design of space-based large-aperture telescopes by introducing a flexible long-rod deployable secondary mirror, thereby lessening the overall structural mass [115]. Tawara et al. leveraged reflective optics to create a compact, high-efficiency space telescope, further reducing structural mass [116].

Regarding vibration isolation and precision pointing, Sacks et al. [117] developed an LUVOIR-type observatory architecture in which the optical telescope assembly is mechanically decoupled from the spacecraft bus, thereby preventing disturbances from propagating to the sensitive optics. Building on this structural isolation, a steady-state observation control system integrates multi-rate sensing, line-of-sight and attitude error estimation, and high-bandwidth pointing control to achieve sub-arcsecond stability. The resulting sensing-processing-actuation chain drives fast steering mirrors, non-contact interface actuators, and traditional spacecraft actuators to maintain ultra-stable pointing during scientific observations. Haddox et al. [118] developed a versatile oscillation mechanism for actively canceling structural vibrations. While these novel structures effectively reduce mass and isolate vibrations, their applicability is limited. Further research into universal vibration isolation mechanisms is imperative to alleviate the pressure on suppressing vibrations in these colossal spacecraft.

Novel steering strategies ranging from vibration-free actuation concepts to structurally isolated architectures have demonstrated clear benefits in reducing disturbance transmission and improving pointing stability in simulation and prototype-level studies. These approaches work well for specific mission environments, but their limited torque authority, environmental sensitivity, or structural constraints prevent broad applicability across super-large platforms. Consequently, while promising, current techniques remain at a partially mature stage and require further generalization to meet the demands of diverse large-spacecraft configurations.

3.2.3 *Health monitoring and condition assessment of large-scale spacecraft*

The health assessment of super-large spacecraft has garnered attention from scholars due to their heightened vulnerability to space debris impacts compared to conventional spacecraft and their far superior capacity to withstand disturbances and collisions in space [119].

Conventional spacecraft exhibit low tolerance to debris impacts and mechanism failures, often resulting in immediate inoperability upon such events. In contrast, mega-structure spacecraft can partially withstand debris impacts and mechanism failures, posing challenges in accurately assessing their health status. Scholars have addressed this issue by developing health assessment systems tailored to different super-large spacecraft mechanisms. These systems utilize spacecraft attitude control capabilities and functionality as indicators, providing a framework to describe component damage and degradation. These diverse health assessment systems comprehensively evaluate the spacecraft's condition [120]. Wu et al. [121] advanced the safety analysis of long-duration crewed spacecraft by constructing a probabilistic survivability assessment framework for pressurized modules. This method integrates debris-environment sampling, impact modeling, penetration and damage evaluation, and a sequence of loss-of-function checks to determine crew and vehicle survivability under hypervelocity impacts. Failure classification is based on critical perforation diameters, crack lengths, and debris-size thresholds that may trigger depressurization, crew injury, or catastrophic structural loss. Wang et al. introduced relevant damage coefficients to describe component degradation processes and established a component reliability model for satellite attitude control systems [122]. Furthermore, Cai et al. leveraged extensive in-orbit telemetry data to develop a clustering storage system and an autonomous health assessment system, collectively forming a comprehensive health evaluation framework for spacecraft [123]. While the studies above primarily focused on developing health assessment systems tailored to specific spacecraft types, some scholars proposed universal health monitoring sensors. For instance, Hofmann et al. presented a flexible sensor for impact detection, which successfully determines impact size and location and predicts impact energy [124].

Existing health-monitoring frameworks have proven effective in diagnosing degradation, evaluating survivability, and detecting impact events across various large-spacecraft architectures, showing strong potential for supporting long-duration missions. Nevertheless, most studies target specific structures or subsystems, and universal assessment standards or integrated multi-modal sensing systems are still underdeveloped. Thus, despite encouraging results, the overall maturity of health assessment remains incomplete and demands further validation under realistic on-orbit conditions.

4 Spacecraft structural dynamics and control for intelligent and adaptive space systems

4.1 Methodological evolution of structural dynamics and control

The field of structural dynamics and control has undergone a steady methodological evolution, driven by the need to model increasingly complex mechanical systems, capture their nonlinear and multi-scale behaviors, and design controllers that remain reliable under real-world operating constraints. Early developments focused on establishing accurate dynamic formulations and efficient numerical integration schemes, such as symplectic algorithms, that preserve the underlying physical structure of the system. As application scenarios broadened and system complexity increased, research progressed toward more capable control frameworks and the incorporation of data-driven elements to supplement conventional modeling and control techniques. Subsection 4.1 reviews advances in structural-dynamic modeling, structure-preserving numerical methods, and emerging learning-assisted control approaches while maintaining an emphasis on physical consistency, constraint handling, and practical implementability.

4.1.1 *Structural dynamic modeling and reduced-order techniques*

Structural dynamics is a branch of mechanics that investigates the vibrational issues of structures under dynamic loads, focusing on the calculation theories and methods for internal forces and displacements within structures when subjected to dynamic loads. In the latter half of the 18th century, Swiss mathematician Leonhard Euler pioneered the study of lateral vibration differential equations for prismatic rods; he solved the equation and established a formula for calculating the natural frequency of lateral vibrations. In 1878, Lord Rayleigh of the United Kingdom elaborated on the vibration theory of elastic bodies such as rods, beams, shafts, and plates, introducing the renowned Rayleigh method. In 1908, Swiss mathematician W. Ritz proposed an approximate method for solving variational problems, later known as the Rayleigh-Ritz method. In 1928, S.P. Timoshenko summarized the theory of elastic body vibrations and its applications in engineering. Over the past few decades, the rapid advancements in aerospace and other technologies have proposed numerous novel structures. The structural dynamics modeling of these structures in complex environments is crucial for precise system control. Traditional methods are increasingly inadequate for the demands of increasingly complex new structures and nonlinear systems, necessitating more accurate, stable, and efficient structural dynamics modeling methods.

Structure-preserving and symplectic algorithms. Symplectic algorithms are numerical methods constructed within the framework of Hamiltonian mechanics. Their core feature is the ability to preserve a series of invariants in the dynamic evolution of the Hamiltonian system, particularly the preservation of the system's symplectic structure, which ensures the stability and accuracy of numerical computations. These algorithms have widespread applications across various fields, especially in optimal control of spacecraft attitude motion and simulation of multibody dynamics systems. In these applications, symplectic algorithms effectively reduce numerical errors and maintain the system's physical structure, which is crucial for long-term numerical simulations. Since the introduction of symplectic algorithms for Hamiltonian systems by Academician Feng Kang, the advantages of symplectic algorithms in preserving the symplectic geometric structure of Hamiltonian systems, conserving the system's total energy, and maintaining constraint conservation have been widely recognized. Zhong et al. [125] developed an adaptive neural-network-based control strategy for electro-hydraulic-actuated manipulators, aiming to address nonlinear dynamics and actuator uncertainties inherent in single-rod EHA mechanisms. Zhong et al.'s controller incorporates prescribed-performance constraints, RBF neural-network approximation, and online weight adaptation to ensure that joint trajectories satisfy accuracy and transient requirements. This integrated framework enables robust tracking performance across multiple joints, even in the presence of actuator nonlinearities and unknown external loads. Deng's team [126] at Northwestern Polytechnical University and Wu's team [127] at Sun Yat-sen University, based on the academic ideas of symplectic algorithms, have proposed symplectic computational methods for nonlinear constrained Hamiltonian systems and symplectic analysis methods for wave propagation, researching structural dynamics analysis and design methods for super-large spacecraft.

Overall, recent developments confirm that symplectic algorithms reliably preserve geometric invariants and deliver stable long-horizon simulations for spacecraft dynamics, demonstrating clear advantages over conventional integrators. Their effectiveness is well established in structural dynamics, multibody simulation, and constrained Hamiltonian systems, yet most applications remain concentrated in controlled numerical studies rather than full mission-scale implementations. Thus, while symplectic methods exhibit strong numerical maturity, further work is needed to integrate them seamlessly with real-time control frameworks and large-scale spacecraft models under broader operational uncertainties.

4.1.2 *Learning-assisted structural control and vibration suppression*

Spaceborne flexible structures operate under physical and operational conditions that differ fundamentally from ground-based or laboratory systems. On-orbit excitation is sparse, leading to limited observability of structural modes and disturbance transmission paths; sensor placement is tightly constrained by deployment geometry, thermal shielding, and mass-power budgets; thermo-elastic drift evolves slowly yet accumulates over long durations; and strict pointing and stability constraints place tight bounds on allowable vibration, actuator authority, and estimation error. In this environment, data availability is limited, uncertainty is significant, and verification under realistic conditions is difficult. AI-enhanced structural control in space therefore focuses not on generic autonomous behavior, but on reinforcing physics-based structural modeling, modal estimation, and constraint-aware control with learning components that remain reliable under sparse excitation and mission-level constraints. This subsection adopts this perspective and examines architectures in which learning augments, rather than replaces, established structural-dynamics models, while supporting uncertainty characterization, reproducible evaluation, and on-orbit admissibility.

Neural network-assisted robotic arm control. Neural networks, a machine learning technology that mimics the human brain's neural networks, play a crucial role in robotic arm control. They identify phenomena, weigh pros and cons, and draw conclusions using processes that mimic the collaborative work of biological neurons. Their strong fitting capability in various nonlinear relationships, achieved through training with a large amount of sample data, has led to numerous studies applying them to traditional control. This application has significantly enhanced control performance, particularly in robotic arm control. Due to their high structural rigidity, robotic arms offer high positioning accuracy and stability, making them suitable for various industrial and service sectors. However, the inherent characteristics of robotic arms, such as strong coupling and strong nonlinearity, along with uncertain parameters within the system, can affect the accuracy of their dynamics and kinematics models. Additionally, the environments in which robotic arms operate often include external time-varying disturbances and model uncertainties, making high-precision control challenging. Over the past five years, the application of neural networks in the field of robotic arm control has become more in-depth, focusing on solving two main issues: first, using neural networks to fit the uncertain parameters of the robotic arm system, as demonstrated by Guo et al. [128] who used radial basis function neural networks in conjunction with traditional backstepping control (TBC) to train the unknown model dynamics of the manipulator, replacing the known dynamics in the reverse iteration; He et al. [129] used barrier Lyapunov functions to handle output constraints and adaptive neural networks to approximate the dead zone function and unknown models of the robotic manipulator; Chen [130] applied neural networks to the PID control of rigid robotic arms, using the self-organizing and learning capabilities of the neural network control algorithm to adjust its control parameters online, achieving effective control of complex controlled objects and online self-tuning of PID parameters, thereby improving system response speed and control accuracy, and effectively reducing tracking errors. Second, using neural networks to compensate for model errors or external disturbances, Yao et al. [131] used radial basis function neural networks to compensate for uncertain items and external disturbances in the model, employing auxiliary anti-saturation functions to address the limited control input, and using dynamic surface control methods to obtain a complete system control law; Man et al. [132] proposed using adaptive RBF neural networks to learn the upper limits of system uncertainties, then using the neural network's output as compensator parameters, to a certain extent, eliminating the impact of system uncertainties and achieving asymptotic error convergence in the closed-loop robotic control system; Wan et al. [133] proposed a neural network-based adaptive controller, using neural networks to approximate the unmodeled dynamic characteristics and unknown disturbances of the robotic arm.

Recent neural-network-assisted controllers reliably enhance tracking accuracy and disturbance rejection for rigid robotic arms, with most studies reporting clear improvements over purely model-based baselines. Their effectiveness is well established in simulations and small-scale experiments, particularly for compensating uncertainties and adapting to nonlinear dynamics. However, their dependence on training data and limited validation on high-DOF, high-speed manipulators indicate that current methods while promising are not yet fully matured for safety-critical or time-sensitive industrial deployments.

Reinforcement learning-assisted robotic arm control. Reinforcement learning algorithms are an essential branch of machine learning, primarily used to describe and solve how an agent learns strategies through interaction with the environment to maximize rewards or achieve specific goals. The most significant feature of reinforcement learning algorithms in structural control is their focus on the feedback from the agent's interaction with the environment, gradually optimizing its behavioral strategies without needing extra attention to its characteristics. The emergence of flexible robotic arms can adapt to more complex working environments and unconventional task scenarios. However, the increased flexibility leads to increased elastic deformation and vibration, further expanding the uncertainty in the system and making precise modeling of the robotic arm challenging. Over the past five years, reinforcement learning has provided new ideas for the accurate control of flexible robotic arms: adjusting strategy parameters based on historical or real-time learning experience data to maximize expected rewards, allowing for the disregard of complex dynamic models of flexible materials, suitable for unstructured environments and interactive tasks. Jiang et al. [134] used the Q-learning method to control the honeycomb pneumatic arm and its interacting environment. However, it has issues with slow operation and lack of stability but a better ability to cope with environmental uncertainties. It does not require analysis of the soft arm to find regularities and modeling. Liu et al. [135] proposed a trajectory planning method for multi-segment continuum robots based on DDPG reinforcement learning, overcoming the traditional method's need for complex modeling and controller design and addressing the issue of joint angular velocity being too large due to matrix inversion singularity, which can damage the drive mechanism, ensuring smooth movement. Zhu et al. [136], in response to the increased environmental uncertainty factors and difficulties in modeling faced by robotic arm path planning in unstructured environments, proposed a dynamic path planning method for robotic arms based on the improved PPO algorithm, capable of adapting to changes in the number and position of obstacles in the scene, and has faster convergence speed and stability than traditional PPO algorithms.

Reinforcement-learning-based controllers show strong potential in handling uncertainty, complex environments, and under-modeled flexible manipulators, and most studies demonstrate feasible trajectory planning and adaptive behavior without explicit dynamic models. Nonetheless, many RL schemes suffer from slow convergence, high sample demand, and limited stability guarantees, restricting their practicality in real-time robotic applications. Overall, RL-assisted control remains an emerging direction: effective in concept demonstrations but still requiring further robustness, safety, and efficiency improvements before widespread adoption.

4.2 Specialized and mission-specific spacecraft structures

4.2.1 *Biomimetic and robotic systems for space applications*

Biomimetic robots are designed to emulate living organisms and perform tasks that leverage biological characteristics. Their design and fabrication are inspired by biological entities, aiming to replicate and mimic their structures and functions, reflected in their shape, movement, and simulation of specific biological traits. Due to the complexity and unpredictability of the biological world, biomimetic robots face control challenges such as motion planning, posture control, and adaptive control during their design. Addressing these issues requires precise mathematical models and complex algorithms.

Micro-scale biomimetic robotic structures. Micro-scale biomimetic robots typically have a body size smaller than 5 cm, allowing them to move freely in confined spaces, such as in minimally invasive surgery in the medical field, precision manufacturing, and aviation engine maintenance. However, robots traditionally powered by motors and other actuators are often too large and heavy to achieve true “micro-scale biomimesis”. Yan’s team at Beihang University [137] developed an insect-scale microrobot powered by an electrostatic vibration-driven microactuation mechanism, enabling high-frequency leg swings through a flexible-beam and magnetic transmission structure. This robot’s asymmetric front-rear leg design, four-bar linkage, and cantilever-coil actuation enable complex stance phases, including squatting, bouncing, aerial motion, and landing, to be coordinated at sub-millisecond timescales. By independently actuating the front legs via wireless control, the BHMbot achieves agile locomotion with diverse trajectories such as circular, rectangular, letter-shaped, and obstacle-crossing paths. In 2015, Shanghai Jiao Tong University successfully developed a milligram-scale electromagnetic actuated biomimetic insect flapping-wing uncrewed aerial vehicle [138], with a prototype weighing 80 mg, a wingspan of 35 mm, a flapping angle of 140°, and a flapping frequency of 80 Hz. In 2017, Shanghai Jiao Tong University proposed an integrated design and manufacturing method where integrated components can transition from a planar state to the required three-dimensional structure, with a prototype weighing 80 milligrams and successfully taking off [139].

Recent micro-scale biomimetic robots demonstrate impressive locomotion agility and functional diversity, confirming that electrostatic, electromagnetic, and origami-inspired actuation can work effectively at insect scale. However, most prototypes remain constrained by limited actuation authority, high power consumption, and short operational endurance, indicating that the technology is still in a developmental phase. Overall, while current designs validate feasibility, substantial advances in miniaturized actuation, energy storage, and integrated control are required before micro-scale biomimetic robots achieve operational maturity.

Soft biomimetic robotic structures. Modeling, perception, and control of soft continuum robots present significant and complex challenges in robotics. Soft continuum robots inherently possess high degrees of freedom and redundancy, making it difficult to ensure both speed and accuracy in numerically approximating their nonlinear partial differential equation models. Environmental perception for soft continuum robots also faces challenges, such as difficulty matching Young’s modulus of sensing circuits with the robot’s body and the design of functional structure distribution. These challenges underscore the complexity of the field and the need for innovative solutions. Various biological organisms in nature provide new inspiration for the modeling and control of soft robots, emulating the high flexibility of biological entities to perform dexterous movements in complex spatial environments and accomplish various tasks. Compared to traditional rigid robots, soft biomimetic robots can better adapt to environmental changes, demonstrating unprecedented adaptability. Must et al. [140] from the Italian Institute of Technology created the first soft robot that mimics the reversible tendril-coiling behavior of climbing plants by leveraging the biological principle of osmosis-driven turgor modulation. This design abstracts plant cell mechanics, where ion transport and osmotic pressure reversibly reshape cellular volume, into an engineered actuation unit composed of flexible porous electrodes, an ion-permeable membrane, and an electrolyte chamber. By regulating ion electrosorption to induce controlled water permeation, the robot achieves reversible bending and tendril-like coiling motions, enabling plant-inspired locomotion and anchoring functions. Li’s team at Beihang University [141] combined the bending motion transfer mode of an octopus’s tentacles and the strategy of capturing prey, proposing and creating a prototype of an octopus-arm robot with integrated sensing circuits, achieving an octopus-like sensing, motion, and environmental interaction operation mode. Li from Harbin Engineering University and Li from Zhejiang University drew inspiration from the physiological structures of deep-sea creatures that adapt well to extreme environments, designed a soft deep-sea robotic fish with a length of 22 cm and a wingspan of 28 cm [5]. They pioneered the pressure adaptation theory and system design methods for deep-sea soft robots, achieving for the first time internationally the actuation of a soft robot without a pressure-resistant shell at 10900 m in the Mariana Trench and autonomous navigation at 3224 m in the South China Sea.

Soft biomimetic robots have exhibited remarkable adaptability and environmental compliance, with recent demonstrations confirming effective plant-inspired coiling, octopus-like manipulation, and deep-sea operation without rigid pressure shells. These results highlight strong functional potential, yet modeling complexity, sensing-actuation integration, and real-time control challenges still limit practical deployment. Consequently, soft biomimetic systems though highly promising, remain in an emerging stage where foundational breakthroughs are still needed to achieve robust, predictable performance in unstructured environments.

4.2.2 *Super-large spacecraft structures*

Superlarge spacecraft are vital space infrastructure for space resource exploration and utilization and are significant strategic aerospace equipment for achieving the goal of becoming a space power. These structures' massive size and weight present challenges in in-orbit operation, such as attitude-orbit-structure coupling and in-orbit attitude control. Additionally, the large scale, configuration changes, and interactions with the space environment produce extremely complex structural vibrations and unique wave phenomena associated with large structures. These factors pose new challenges for dynamic modeling and numerical solutions, precise in-orbit attitude control, low-frequency structural vibration suppression, and regulating vibration-flutter coupling characteristics.

Orbit-attitude-structure coupling and co-design. For very large and super-large spacecraft structures, orbit-attitude-structure (OAS) integration must account for several coupled effects that evolve during on-orbit assembly and long-term operations. As the structure grows, configuration parameters and boundary conditions change over time, while attitude maneuvers introduce load redistribution and solar-radiation-pressure disturbances that accumulate into slow orbital drift. Structural vibration and base flexibility propagate into sensing and pointing channels, and distributed sensing-actuation architectures introduce latency and asynchrony. Thrust-structure interaction further couples high-level orbit planning with local structural dynamics. These features define the three key interfaces in the integrated model: structural modes affecting attitude motion, attitude pointing affecting orbit evolution, and orbit-dependent environmental forces feeding back into structural response. Against this background, high-level research directions include physics-consistent model identification with residual-error modeling, learned observers and prognostics and health management (PHM)-driven closed-loop strategies, learning-aided SCP and MPC with runtime assurance, configuration control co-design, and distributed cooperative control for multi-module assemblies. From a control perspective, the asynchronous evolution of configuration, sensing, and actuation in super-large spacecraft motivates intermittent, event-triggered, and safety-oriented control frameworks. Along this line, recent studies have pioneered event-triggered adaptive safe boundary control for uncertain distributed-parameter systems under intermittent actuation, and subsequently marked a notable advance in distributed nonlinear control by extending intermittent-feedback adaptive schemes to time-varying systems with mismatched uncertainties [142,143]. Furthermore, minimal validation items for on-orbit readiness involve demonstrating uncertainty coverage, constraint feasibility and safety, end-to-end timing and compute-budget satisfaction, and clearly defined fallback rules.

During the on-orbit operation of space solar power stations, the microwave emission antenna needs to maintain a geostationary attitude. In contrast, the solar cell array must maintain a sun-pointing attitude. However, under the influence of distributed space disturbance forces, centralized or decentralized control forces, and distributed inertial forces, a unique OAS coupling phenomenon occurs, making it difficult to decouple attitude control. Li et al. [144, 145] systematically investigated how orbit and attitude affect the deformation and vibration of sun-facing structural beams, which compares the dynamic response under different quasi-sun-pointing swing patterns. Through symplectic-integration analysis, they demonstrated that a quasi-sun-pointing attitude generates a linearly distributed lateral inertial force along the beam-opposite in direction to the first-order gravitational expansion, reducing the maximum control torque to merely 0.67% of that required for strict sun-pointing [144, 145]. Building upon these dynamics, they [146] further proposed a switching iterative learning control method that exploits the periodic nature of orbital disturbance torques, achieving an order-of-magnitude improvement in pointing accuracy while simultaneously reducing sensor-noise sensitivity by an order of magnitude. Chen et al. [147] proposed a concept design for a free-floating space solar power station, which adopted a sun-frozen orbit in the Earth's geosynchronous Laplace orbital plane and a quasi-sun-pointing attitude. Solving the system's attitude-orbit coupling model with an energy-preserving-constraint-preserving algorithm found that almost no orbit and attitude control is needed during on-orbit operation, saving about 95% of control fuel.

Across recent studies, integrated OAS modeling has shown clear effectiveness in revealing coupled disturbance mechanisms and guiding control design, with several studies demonstrating significant reductions in required control torque and marked improvements in pointing accuracy. These results confirm that physics-aware coupling models can successfully capture critical interactions in super-large structures, yet most validations remain simulation-based and limited to specific configurations. Consequently, while the methods exhibit strong conceptual and numerical maturity, further on-orbit demonstrations and broader uncertainty characterization are still required before fully integrated OAS control can be considered operationally mature.

Design and dynamic control of super-large deployable space structures. Due to the limitations of rocket launch capabilities and envelope constraints, large space structures must be folded into a minimal volume before launch, then unfolded and assembled to form an integrated structure after entering orbit. This requires modular design of large space structures, with substructures with high packing ratios and stable, reliable deployment and retraction properties. In recent years, new deployable structures, such as origami structures, have received significant attention in modularizing substructures for large space structures. These structures are characterized by complex configurations and numerous nonlinear constraint equations, posing significant challenges for dynamic modeling and precise solutions.

Li et al. [148] investigated deployable thick-plate origami by introducing a natural-coordinate representation capable of capturing the geometric configuration and hinge-thickness constraints of various folding patterns for thick Miura, thick diamond, and thick waterbomb units. Based on this unified geometric description, they formulated constrained Hamiltonian dynamic equations that rigorously preserve the structural compatibility during folding and deployment. The framework enables accurate prediction of dynamic responses in complex thick-origami mechanisms, supporting the design of large-scale deployable space structures with enhanced rigidity and controllability. Zhao et al. [149], with the background of large space solar panels and antenna structures, equivalently represented the mountain and valley lines in Miura origami as spatial beam structures and used the wave propagation symplectic analysis method for periodic structures to calculate the band structure of the origami lattice metamaterials. They solved the differential-algebraic equations using an energy-preserving-constraint-preserving algorithm, analyzing the free deployment process of common thick plate origami structures driven by torsion springs.

Recent progress in deployable origami structures and geometric-constraint-preserving dynamics has enabled accurate prediction of folding kinematics and improved controllability for large-scale space assemblies, demonstrating good agreement with theoretical and numerical benchmarks [150]. These methods work well for thick-plate origami, modular deployable units, and dynamic folding processes, yet their maturity is limited by challenges in scalability, hinge-parameter uncertainties, and real-time control during deployment. Overall, the approaches are promising and technically sound but still require expanded experimental validation and robustness studies before supporting full-scale flight systems.

5 Conclusion and future research directions

Over the past decade, spacecraft dynamics and control have undergone substantial methodological and technological evolution, driven by increasingly complex mission objectives, expanding system scales, and growing autonomy requirements. This review, commemorating the publication of the Spacecraft Dynamics and Control Series, has synthesized recent advances across orbital dynamics and optimization, attitude and formation control, structural dynamics, and learning-assisted control methodologies. Rather than treating these developments as isolated threads, the review has emphasized their emerging integration patterns, clarified their respective roles and limitations, and highlighted how physical consistency and constraint awareness continue to underpin reliable spacecraft operation.

Beyond summarizing the current state of the art, this review has also examined how these research directions are likely to evolve in response to future space-mission demands. To complement the narrative discussion, Table 2 provides a structured forward-looking comparison of expected developments over five-year and ten-year horizons. The table distills each major domain into concise trend descriptors together with their primary driving factors, emphasizing a progressive transition from engineering-level autonomy toward system-level coordination under increasingly stringent physical, operational, and safety constraints. By juxtaposing mid-term and long-term trajectories, it clarifies how present-day techniques may mature into more scalable, coordinated, and resilient frameworks, while reinforcing, rather than reiterating, the conclusion drawn in the main text.

From an orbital-dynamics perspective, future research is expected to move beyond single-mission optimality toward multi-objective, long-horizon design in cislunar and Earth-Moon space. Reusable low-energy transfers, persistent logistics chains, and cross-orbit asset coordination will increasingly shape trajectory design, placing greater emphasis on robustness, scalability, and supervisory autonomy. These trends reflect a shift from isolated optimization problems to interconnected orbital-transport architectures, where physical feasibility and operational reliability remain decisive factors.

In attitude and formation control, the growing complexity of spacecraft roles and interactions highlights the importance of coordination-aware control architectures. Strong coupling among orbit, attitude, and structural dynamics, together with the rise of dense satellite clusters and non-cooperative operational scenarios, demands control strategies that explicitly account for multi-agent interaction, disturbance propagation, and verification requirements. Propellant-less formation flying, autonomous reconfiguration, and inspection or capture of uncooperative targets exemplify this evolution, underscoring the need for robust, constraint-consistent control frameworks rather than purely performance-driven solutions.

Structural dynamics and control are likewise transitioning from predominantly planar or weakly coupled configurations toward three-dimensional, highly flexible architectures with increasing functional integration. Adaptive deployables, variable-stiffness mechanisms, and embedded sensing-actuation grids point toward future kilometer-

Table 2 Five-year vs. ten-year forward trends in spacecraft dynamics and control.

Domain	Five-year trend	Ten-year trend
Orbit dynamics	Multi-objective cislunar design; reusable low-energy transfers; initial Earth-Moon logistics automation.	Autonomous cislunar traffic management; cross-orbit asset orchestration; self-optimizing orbital transport networks.
Driving factors	Lunar traffic; fuel reduction; operational robustness.	Lunar economy; persistent presence; Scalable autonomy.
Attitude & formation control	Coupled orbit-attitude control; Hybrid formations; autonomous geometry reshaping; embedded cooperative control for small clusters.	Self-maintaining formation constellations; game-theoretic multi-agent coordination; non-cooperative capture/inspection; defense-oriented maneuver intelligence.
Driving factors	Cost pressure; propellant minimization; Reliability requirements; Precision geometry control; Baseline autonomy for routine tasks.	High-density traffic risk; adversarial conditions; escalation from situational awareness to defense-oriented operations; persistent surveillance needs; autonomous decision superiority.
Structural dynamics	Adaptive deployables; variable-stiffness mechanisms; low-order vibration suppression; onboard PHM integration.	Kilometer-scale intelligent structures; embedded sensing-actuation grids; real-time OAS co-design; structural autonomy for long-duration missions.
Driving factors	Large flexible arrays; modular assembly; Thermo-elastic disturbances.	Next-gen power stations; large interferometers; permanent orbital infrastructure.
AI-driven control	Trusted learning-in-loop; Runtime assurance; Lightweight onboard inference; Hybrid model-data fusion.	Self-evolving control agents; uncertainty-resilient planning; Earth-space federated intelligence; fully autonomous mission execution loops.
Driving factors	Autonomy requirement; sim-to-real gap; Limited onboard resources.	Data scale; operational uncertainty; Distributed spacecraft swarms.

scale structures that require real-time co-design of orbit, attitude, and structural dynamics. These developments elevate health monitoring, vibration suppression, and long-term structural autonomy from supporting roles to central design considerations, particularly for missions involving permanent orbital infrastructure or super-large observatories.

Across all domains, artificial intelligence is increasingly positioned as an enabling technology rather than a replacement for physics-based modeling and control. Current trends indicate a convergence toward trusted learning-in-the-loop paradigms, where lightweight data-driven components enhance model-based solvers through initialization, uncertainty characterization, or decision support, while hard constraints and safety guarantees remain enforced by classical methods and runtime assurance mechanisms. As reflected in Table 2, longer-term developments are expected to emphasize layered autonomy, uncertainty resilience, and distributed coordination across spacecraft networks, rather than fully unconstrained autonomy.

Taken together, the trends summarized in this review suggest that future spacecraft dynamics and control will be defined less by isolated algorithmic advances and more by the integration of modeling, control, autonomy, and verification across scales and mission phases. Despite significant progress, the translation of these advances into dependable, flight-ready systems remains constrained by challenges in verification, scalability, and cross-domain coupling. Addressing these challenges will require continued emphasis on physics-consistent modeling, constraint-aware control architectures, and systematic validation, ensuring that increasing autonomy and system complexity are matched by corresponding gains in reliability and operational confidence.

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