Hindawi
International Journal of Aerospace Engineering
Volume 2024, Article ID 4650731, 13 pages
https://doi.org/10.1155/2024/4650731

Research Article

ACP-Based Space Systems: Design, Development, and Operation

Yingkai Cai, Qingliang Meng, and Zhaokui Wang

School of Aerospace of Engineering, Tsinghua University, Beijing 100084, China

Correspondence should be addressed to Zhaokui Wang; wangzk@tsinghua.edu.cn

Received 28 November 2023; Revised 17 February 2024; Accepted 8 March 2024; Published 27 March 2024

Academic Editor: Vijayanandh Raja

In the context of the rapid advancements in space technology and the increasing complexity of space missions, there is a growing need for efficient and effective approaches to tackle the multifaceted challenges faced by space systems. Traditional methods often fall short in providing comprehensive support throughout the entire life cycle of space systems. To address these challenges, this paper presents a novel parallel space system architecture based on ACP (artificial systems, computational experiments, and parallel execution) and explores its applications in the design, development, and operation of space systems. The proposed architecture integrates artificial systems with actual space systems and employs computational experiments to generate extensive sample data. This approach enhances the accuracy of the artificial systems' model and optimizes the performance of the real systems, facilitating parallel advancements between the two. The design, development, and operation processes of Q-Sat, implemented using the ACP framework, serve as a case study to illustrate the advantages of parallel space systems. Following adjustments made to the discrepancies between parallel systems under the ACP-based space system framework, the accuracy of missing orbit compensation improved by 86.5%, and the 24-hour forecast positional error was reduced by approximately 65 m. Furthermore, this paper discusses future trends, emphasizing the increasing efficiency and reliability of digitized, integrated, and adaptive space systems. The findings contribute to the understanding of parallel space systems and provide valuable insights for further advancements in the field.

1. Introduction

Space systems are complex and large-scale systems, consisting of the space environment, spacecraft, ground system, and support system [1]. With continuous technological advancements, the types of space missions have become increasingly diverse [2, 3]. Moreover, spacecraft development has evolved from a single system with a single mission to include multisatellite systems, such as satellite constellations, distributed formation satellite systems, and cluster spacecraft [4–6]. These advancements have led to more complex interactions among spacecraft within multisatellite systems. Additionally, the autonomy of spacecraft has been enhanced, which has further driven the need for interaction between different spacecraft systems. Furthermore, the space environment has been continuously deteriorating, leading to increased uncertainties faced by space systems [7]. As a result, future space systems are increasingly exhibiting the characteristics of complex systems [8]. The architecture design, development, and operation of such a complex system will become crucial.

In current research on space systems, significant progress has been made in the development of spacecraft simulation. The European Space Agency (ESA) has developed the SMP2 Spacecraft Simulation Platform, which has become the de facto standard in the European space simulation community. Simulation software such as EuroSim and SIMSAT, which adhere to the SMP2 standard, is widely used in the field [9]. The Netherlands Space Office has developed the configurable simulation system framework tool called EuroSim Framework. It enables the construction of configurable simulators for digital simulations and has been extensively applied to ESA satellite projects, including GAIA and Galileo. The NASA Johnson Space Center has spearheaded the development of the Trick General-purpose Simulation Environment, which is an open-source project. It has been applied in flight control tasks for projects such as the Orion spacecraft and the Space Station robotic arm [10]. The Jet

Propulsion Laboratory (JPL) has utilized Dshell and Darts to establish a general purpose simulation environment that includes the Darts library for flexible multibody dynamic calculations and a component model library. This simulation environment is platform-independent and has been employed in models such as Cassini and Galileo [11]. These research efforts highlight the high level of maturity achieved in terms of accuracy, real-time performance, and interactivity in spacecraft simulation systems.

In addition to these developments, the advent of digital thread and digital twin concepts has paved a new pathway for mapping physical space entities to virtual space solutions [12, 13]. In the aerospace domain, Siedlak et al. proposed an integrated digital thread approach encompassing detailed models and analyses, capable of quantifying and trading off unconventional design production costs, rates, and efficiencies in the early stages of the design process within a variable demand environment [14]. Zhang et al. established a digital thread-based digital twin (DTDT) framework, addressing the complexities and management challenges of aircraft assembly environments, thereby enhancing the efficiency of the aircraft assembly process [15]. Eskue proposed a digital thread roadmap for manufacturing and health monitoring the life cycle of composite aerospace components, aiming to garner exponential benefits for life cycle insight and manufacturing optimization [16]. Further, Zhao et al. proposed an application of digital thread in model-based spacecraft development, offering solutions to the challenges of diverse data types, complex relational interconnections, and sharing difficulties prevalent in various stages of the development process [17].

However, there is currently no unified framework for studying the design, development, and operation of space systems. Therefore, it is necessary to construct a comprehensive framework guided by system theory, which encompasses multiple stages, objectives, and hierarchical levels. In addressing the modeling, analysis, control, and management challenges of complex systems, Wang has proposed a theoretical framework and methodology centered around artificial systems, computational experiments, and parallel execution, guided by the principle of continuous exploration and improvement [18, 19]. This approach allows for the resolution of modeling, analysis, and experimentation issues within a unified theoretical framework and has found wide application across various domains. For instance, in the field of complex engineering, it has been applied to real-time safety monitoring of visual intelligence [20], transportation systems [21], oil fields [22], metaverse [23], and so on [24–27]. In agricultural engineering, it has been utilized for monitoring and managing crop cultivation, precision control of crop manufacturing, and fine control of high-value plant species [28]. In the realm of ecological environment, it has been employed for experimental ecosystem transformation, regulation of river and mountain ecology, and assessment of the impact of human activities on the environment [29]. ACP, proposed as a novel framework in response to the rapid development of complexity science and computer simulation technology, offers an innovative approach to address complex systems in the context of space systems. Specifically tailored to space complex systems, the core idea revolves around the integration of actual space systems and artificial space systems, combining physical experiments with computational experiments. The objective is to optimize space systems across different stages and maximize the utilization of actual experimental data.

Motivated by these facts, this work attempts to construct an ACP-based parallel architecture for space systems that integrates physical experiments with computational experiments to optimize the design, development, and operation of space systems. The contributions of this article are listed in the following aspects.

(1) An ACP-based parallel space systems were established, introducing the concept of parallel design, development, and operation at different stages of the space systems. By creating an artificial system based on the real space system and conducting computational experiments, a vast amount of sample data was generated to accelerate the optimization of the real system. Meanwhile, continual adjustments were made to the artificial system based on feedback from the real space system, achieving parallel progression of both

(2) For Q-Sat, a parallel artificial system based on the in-orbit perturbation model was established during the design phase to facilitate the detection of the gravitational field and upper atmosphere. During the development phase, corresponding artificial systems for each satellite subsystem were constructed for parallel computational experiments. The results obtained were analyzed in conjunction with feedback from the actual system data, gradually refining the artificial system model while supporting the optimization of real system parameters

(3) In the operation phase of Q-Sat, parallel systems for the operational segment were established. Utilizing the extensive data acquired in-orbit by the satellite, the parallel systems continuously corrected the discrepancies between the artificial and real systems while analyzing the data. Through in-orbit experimental data, gravitational field and atmospheric density inversion calculations were performed, and models within the artificial systems were dynamically updated to enhance the accuracy of Q-Sat orbit propagation predictions within the artificial systems

The rest of this paper is organized as follows. The flowchart of the research methodology is shown in Figure 1. In Section 2, the concept of parallel space systems is introduced, and the overall architecture of the ACP-based space systems are established. Then, Section 3 focuses on the design, development, and operation of the Q-Sat using the ACP framework. The results and discussion of parallel experiments of Q-Sat are given in Section 4. Next, Section 5 outlines the future prospects of parallel space systems and potential advancements. Finally, the conclusion of this paper is summarized in Section 6.

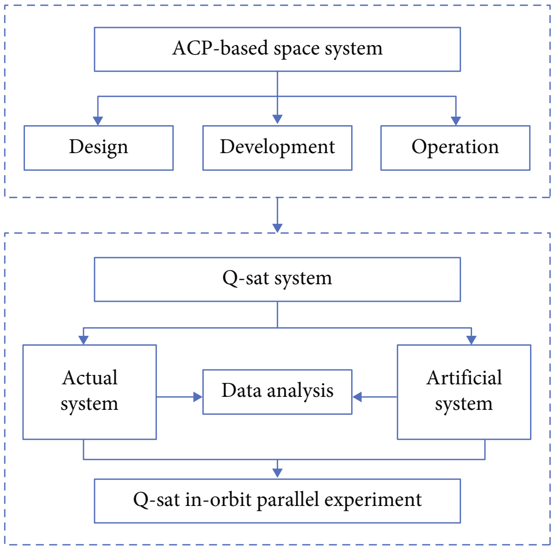

Figure 1: The flowchart of the research methodology.

2. Overall Structure of ACP-Based Space Systems

2.1. Parallel Space System Concept. The parallel space systems are built upon the ACP theoretical framework, wherein artificial systems are developed to correspond to the actual systems. By executing both systems in parallel, a comparative analysis is conducted to evaluate their behaviors, thereby continuously enhancing the model of artificial systems. This methodology significantly contributes to the space systems.

The core principle of parallel space systems lies in the parallel development of actual systems and artificial systems through parallel computational experiments. In the process of designing, developing, and operating space systems, the characteristics of physical experiments vary across different stages. Given the limited number of physical experiments that can be conducted, it becomes challenging to comprehensively capture all key factors. Similarly, when constructing artificial system models, it is difficult to account for all uncertain factors. To address these limitations, conducting various state and influential factor experiments in the artificial space systems based on the results of a single physical experiment offers a cost-effective and adequately diversified approach. Moreover, research on perturbation analysis and exploratory analysis methods tackles the effective utilization of experimental data. Perturbation analysis, in particular, offers an improved alternative to the Monte Carlo method in computational experiments. By introducing perturbation quantities to construct perturbed sample trajectories from existing sample trajectories and analyzing the influence of perturbation parameters on these trajectories, the performance of space systems can be quantitatively assessed.

In contrast to digital twins, parallel systems serve a broader purpose. Digital twins primarily serve as a real-time virtual representation of a physical entity or system [30]. While parallel systems, particularly in the context of space system applications, operate on the ACP theoretical framework, digital twins focus more on synchronizing with the actual systems to provide immediate feedback and control. Digital twins are predominantly used in scenarios where constant monitoring, maintenance, and optimization are crucial, such as in manufacturing processes or infrastructure management. They rely heavily on IoT (Internet of Things) technologies for data collection and are often integrated into the system they mimic for real-time interaction and decision-making.

In the realm of parallel space systems, this distinction becomes more pronounced. For instance, consider a satellite system where the actual systems comprise the physical satellite orbiting the Earth, and the artificial system is its computational counterpart. In a digital twin setup, the virtual model of the satellite would continuously receive data from the satellite's sensors to update its state and predict future conditions, primarily focusing on maintenance and immediate operational adjustments. Conversely, in a parallel space system scenario, the artificial systems would not only replicate the satellite's current status but also run parallel computational experiments. These experiments could explore a wide range of scenarios, like different orbital paths or responses to hypothetical space weather events, which are not feasible or practical to replicate in physical experiments. This approach enables a comprehensive analysis and a deeper understanding of the satellite system's behavior under various conditions, enhancing its design and operational strategies.

The parallel space systems, thus, serve a broader purpose, extending beyond immediate synchronization with the physical system. It creates a more versatile environment for experimentation and analysis, driving innovation and optimization in space system design and operations. This methodology exemplifies the fusion of theoretical research and practical application, offering a robust framework for advancing space technologies.

The parallel space system architecture offers several advantages:

(1) *System Performance Optimization*. The parallel space system architecture enables the evaluation and optimization of space system performance through computational experiments. By conducting simulations and virtual experiments, different parameter settings, algorithm adjustments, and system configurations for each subsystem can be explored to identify the optimal solutions. This approach allows for early detection of potential issues, system design improvements, and the optimization of space system performance and efficiency

(2) *Rapid Iteration and Improvement*. The parallel space system architecture facilitates fast iteration and continuous improvement. Computational experiments and simulations enable quick testing and validation of system designs, providing ample data resources to support actual systems. This promotes timely adjustments and optimizations, accelerating system development, reducing development time and experimental costs, and enhancing system quality and reliability

(3) *Decision Support and Risk Assessment*. The parallel space system architecture provides data analysis and decision support based on computational experiments. By monitoring the real-time status and operation of the system, it becomes possible to better evaluate the health of different stages of the space systems, identify potential issues, and take appropriate measures. This helps reduce risks, enhance system robustness, and enable researchers to make data-driven decisions

The parallel space systems, based on the ACP theoretical framework, innovatively blend actual and artificial systems via parallel computational experiments. By leveraging artificial space systems and techniques like perturbation analysis, it overcomes limitations of physical experiments, enabling a thorough performance assessment. This architecture streamlines system optimization, accelerates iteration cycles, and enhances decision-making and risk assessment. Consequently, it revolutionizes space system development by significantly improving system quality, efficiency, and reliability.

2.2. Phased Parallel Space System Establishment. Given that the application scales within different stages of a space systems vary significantly, the process of establishing artificial systems in a phased manner can effectively partition the entire space systems into discernible levels. This approach serves to underline the distinctions among systems at various levels and facilitates the parallel growth of artificial and actual systems, made possible through parallel computation. In the context of this article, the ACP-based space systems are classified into three distinct, yet interconnected stages: the design phase, the development phase, and the operation phase (see Figure 2).

2.2.1. Design. The design phase marks the inception of a space system's life cycle. During this stage, based on the specifics of the space mission, system objectives and requirements are identified, and solutions are devised along with the formulation of overall parameters. The establishment of an artificial systems in the design phase is primarily used for simulating and assessing the performance and feasibility of different design solutions, mainly including the overall system model and subsystem models. By creating an artificial system model, a high-level exploration and validation of the system's overall architecture, functions, and performance can be conducted. In the design phase, the artificial system model can aid researchers in understanding and optimizing its holistic design, including the distribution of system functions, the interaction among subsystems, and the selection of key technologies. Concurrently, through parallel execution with the actual systems, researchers can conduct a comparative analysis of the behavioral differences between the artificial system model and the actual systems, refining the artificial system model for the design phase based on actual results.

2.2.2. Development. Upon completion of the design phase, the space systems transition into the development stage. This phase involves the transformation of designs into tangible systems, along with manufacturing, integration, and testing. The creation of an artificial systems in the development stage predominantly aids the actual construction and integration process of the system. By establishing an artificial system model, including parallel experimental models of subsystems and an integrated parallel experimental model of the space systems, the performance, interaction, and integration conditions of various system components and subsystems can be simulated and evaluated. On one hand, comparison and analysis with actual system data feedback can detect and resolve integration issues, optimize system performance, and gradually refine the artificial system model to more accurately reflect the behavior of the actual systems. On the other hand, large-scale computational experiments with the artificial system model can assist researchers in identifying and resolving integration problems, optimizing system performance, and implementing necessary adjustments and improvements.

2.2.3. Operation. The operational phase represents the stage where the space systems are deployed and operated to fulfill its mission and objectives. In an ACP-based space systems, this stage supports system operation and optimization through parallel execution with the actual systems. In a departure from previous phases, this component of the artificial systems encompasses the complete space systems, incorporating ground stations, control management, and scientific modeling required for the processing and analysis of space data. During the operational phase, the artificial system model can run synchronously with the actual systems, simulating and evaluating the real-time behavior and performance of the system. By comparing and analyzing against the actual systems, researchers can monitor its operational status, identify potential issues, and promptly make adjustments and optimizations. Concurrently, this parallel execution aids in refining the artificial system model, enabling it to better reflect the behavior of the actual systems and further enhance its performance and efficiency.

Throughout each phase, the parallel space systems enable synchronized development and optimization of the artificial and actual systems via parallel computational experiments. This process of parallel growth optimally leverages the characteristics of the system, refines its design, and evaluates operational improvements. It is important to emphasize that this ongoing process sustainably enhances the performance and efficiency of the system, ensuring progressive advancement throughout the entirety of the space system's life cycle.

3. ACP-Based Design Development and Operation of Q-Sat

3.1. Q-Sat Overview. Q-Sat (shown in Figure 3), a microsatellite meticulously crafted by the Distributed and Intelligent Space System Lab (DSSL) at Tsinghua University, was successfully launched into orbit on August 6, 2020, onboard a CZ-2D rocket [31]. The primary mission objective of Q-Sat is twofold: to detect the gravity field and density of the

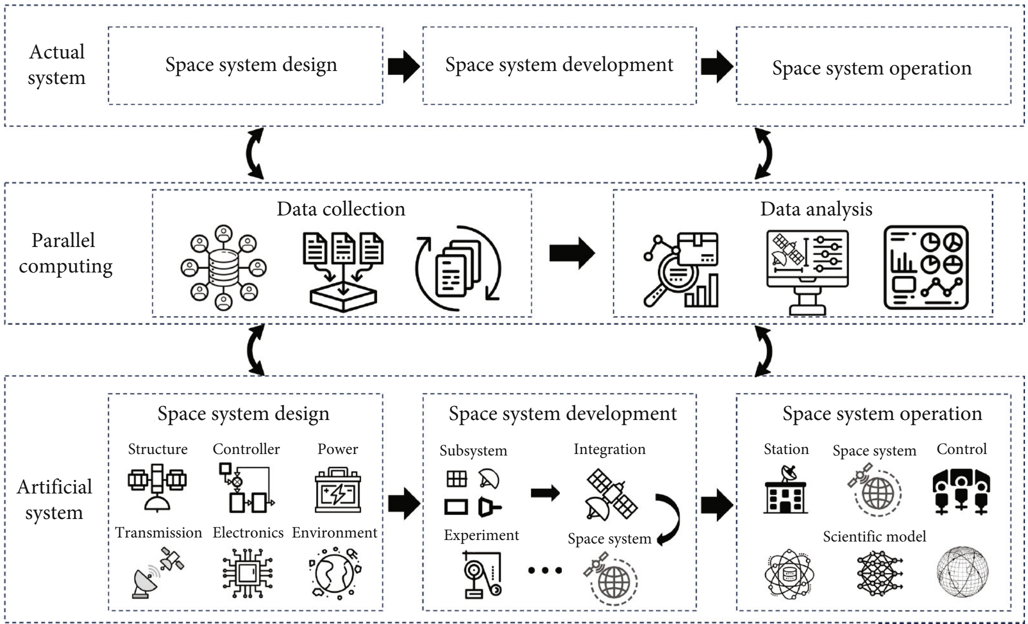

Figure 2: Parallel space systems.

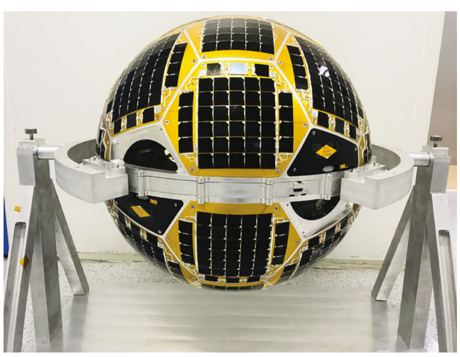

Figure 3: Q-Sat overview.

upper atmosphere of the Earth. Both of them can be simultaneously inverted using a method grounded in dynamic inversion [32].

Built upon the ACP theory, Q-Sat strategically establishes corresponding parallel systems at each pivotal stage of satellite design, development, and operation. By seamlessly executing the satellite system in tandem with the artificial systems, an ongoing cycle of refinement is facilitated for the model of the artificial systems. Consequently, this enhances the overall performance of the Q-Sat satellite system, underscoring the value of parallel execution in system optimization.

3.2. Parallel Design. During the design phase of Q-Sat, parallel artificial systems based on the in-orbit perturbation model were established to enable gravity field and upper atmospheric detecting. By employing this system, simulations were conducted to assess the performance and feasibility of design solutions under various structural and orbital parameters.

To facilitate mission analysis and overall design, a joint estimation model for gravity field and atmospheric density sensing parameters was developed as [32]

$$\Delta \boldsymbol{X} = \boldsymbol{X}^*(t) - \boldsymbol{X}(t) = \frac{\partial \boldsymbol{X}(t)}{\partial \boldsymbol{X}(t_0)}\bigg|_{x(t)} \Delta \boldsymbol{X}_0 + \frac{\partial \boldsymbol{X}(t)}{\partial \boldsymbol{P}}\bigg|_{x(t)} \Delta \boldsymbol{P}, \quad (1)$$

where $\boldsymbol{X}(t)$ is the satellite in-orbit state, obtained by integrating using the dynamical model; $\boldsymbol{X}^*(t)$ is the satellite observation orbit, determined by the satellite precision orbiting load; and $\Delta \boldsymbol{P}$ is the atmospheric and gravity field model correction. It can be seen from Eq. (1) that $\Delta \boldsymbol{P}$ can be inversely solved by the high-precision satellite observation orbit and the dynamic integral orbit. The high-precision dynamic model needs to take into account that the satellite is subjected to uptake forces $\boldsymbol{a}_{\mathrm{sat}}$ in orbit, which can be expressed as

$$\boldsymbol{a}_{\mathrm{sat}} = \boldsymbol{a}_0 + \boldsymbol{a}_{\mathrm{ns}} + \boldsymbol{a}_d + \boldsymbol{a}_{\mathrm{sr}} + \boldsymbol{a}_S + \boldsymbol{a}_M + \boldsymbol{a}_g, \quad (2)$$

where $\boldsymbol{a}_0$ is the central gravitational acceleration, $\boldsymbol{a}_{\mathrm{ns}}$ is the nonspherical perturbation acceleration, $\boldsymbol{a}_d$ is the atmospheric drag perturbation acceleration, $\boldsymbol{a}_{\mathrm{sr}}$ is the solar radiation pressure perturbation acceleration, $\boldsymbol{a}_S$ is the solar gravitational acceleration, $\boldsymbol{a}_M$ is the lunar gravitational acceleration, and $\boldsymbol{a}_g$ is the other perturbation accelerations such as Earth albedo radiation pressure, relativistic effects, and solid Earth tides. These small perturbation accelerations generate magnitudes ranging from approximately $10^{-18}\,\mathrm{m/s^2}$ to $10^{-15}\,\mathrm{m/s^2}$ [33]. In comparison to the primary perturbation accelerations mentioned above, these magnitudes are significantly smaller, allowing for their negligible influence. The atmospheric drag, known as $\boldsymbol{a}_d$, is a nonconservative perturbation force that leads to the continuous decay of the orbital semimajor axis of the spacecraft. It is the primary factor causing a decline in satellite altitude. The acceleration resulting from atmospheric drag can be expressed as [34]

$$\boldsymbol{a}_d = -\frac{1}{2} C_D \frac{A}{m} \rho \boldsymbol{v}_{\mathrm{rel}}^2, \tag{3}$$

where C_D denotes the drag coefficient, which is determined by factors such as the shape and surface properties of the spacecraft. A/m represents the area-to-mass ratio of the spacecraft. ρ represents the high-altitude atmospheric density at the location of the spacecraft, influenced by factors like solar activity and geomagnetic activity. It exhibits characteristics of randomness, real-time variability, and uncertainty. $\boldsymbol{v}_{\mathrm{rel}}$ represents the velocity of the spacecraft relative to the local high-altitude atmosphere. In the analysis of perturbations for low Earth orbit spacecraft, atmospheric drag is the predominant source of uncertainty. It is influenced by factors such as the orbit, structure, and materials of the spacecraft, and it also impacts the energy generation of the satellite's surface solar cells.

To facilitate the refinement of the high-altitude atmospheric density model via the Q-Sat mission, we have selected the Jacchia-Roberts model [35] as the atmospheric density model subject to optimization. Notably, this model demonstrates superior performance in atmospheric density prediction and orbital forecasting missions for orbits under 500 km when compared to other empirical models. The atmospheric temperature at altitude h for the Jacchia-Roberts model is

$$T_h = T_\infty - (T_\infty - T_x) e^{(-((T_x - 183)/(T_\infty - T_x))((h-125)/35)(L/(R_a+h)))}, \tag{4}$$

where T_x is the atmospheric temperature at 125 km height, R_a is the polar radius of the Earth, and L is the correction parameter, which can be approximated by a polynomial function of the atmospheric top-level temperature T_∞,

$$L = \sum_{i=1}^{5} l_i T_\infty^{i-1}. \tag{5}$$

Within the scope of the Q-Sat mission, the parameter l_i represents the model parameter for optimization.

By considering the aforementioned influencing factors, a comprehensive parallel design model for satellites has been established. This model encompasses various aspects, including parameter estimation, perturbation forces, orbit, structure, and energy. Through the utilization of parallel computational experiments, the performance and feasibility of different structural parameters, orbital altitudes, and orbit accuracy can be simulated and evaluated. The results obtained from the parallel computational analysis provide valuable insights for implementing structural modifications and conducting orbit energy reviews in the actual systems. Additionally, the measured values from the Q-Sat actual systems are fed back to the artificial systems to supplement and refine the parameters, facilitating the parallel growth of the artificial systems alongside the actual systems. As illustrated in Figure 4, the parallel design process for Q-Sat involves a cyclical feedback loop, where the artificial systems and the actual systems continuously interact and evolve in parallel. This iterative approach ensures a robust and optimized design that aligns with the mission objectives and performance requirements.

The overall mission parameters of Q-Sat obtained based on the ACP parallel design are shown in Table 1.

Through the integration of parallel computational experiments and the utilization of measured data, the parallel design model for Q-Sat enables informed decision-making, enhanced performance evaluation, and improved feasibility assessment. It serves as a valuable framework for achieving a synergistic and efficient design process in the field of satellite development.

3.3. Parallel Development. During the developmental phase of Q-Sat, the subsystems undergo meticulous design, integration, and testing in alignment with the overall design parameters of the mission. A parallel system approach is implemented, as depicted in Figure 5, wherein corresponding artificial systems are established for each satellite subsystem. These include the structural system, separation system [36], payload system [37, 38], attitude control system, power system [39], electronic system, and data transmission system. To ensure accurate representation of the actual systems, parallel computational experiments are conducted for each subsystem to simulate their performance under various operating conditions. The obtained results are then compared and analyzed against feedback from actual system data, progressively refining the artificial system models. Simultaneously, large-scale parallel computational experiments are conducted to expose potential deficiencies and hazards throughout the subsystem design, processes, manufacturing, and assembly stages. These experiments provide crucial data support for parameter optimization and improvement.

This comprehensive approach facilitates the evaluation and optimization of subsystem performance while effectively identifying and mitigating potential issues and risks throughout the development process. The parallel system framework ensures an efficient and streamlined developmental cycle, culminating in an enhanced Q-Sat design and enhanced overall system reliability.

During the integration and testing phase of satellite systems, the reliability of the satellite necessitates thorough ground experiments. However, due to the limited number of physical tests feasible for the actual systems, it becomes challenging to comprehensively encompass all crucial factors. To maximize the efficiency of ground test data utilization, a satellite simulation flight software and measurement and control analysis software have been designed. These enable the establishment of an integrated parallel testing system, as illustrated in Figure 6. The satellite simulation system facilitates real-time modeling of the orbit and attitude variations postinsertion, considering diverse orbital conditions. It injects real-time orbit and attitude data into the actual satellite system and testing equipment. The testing

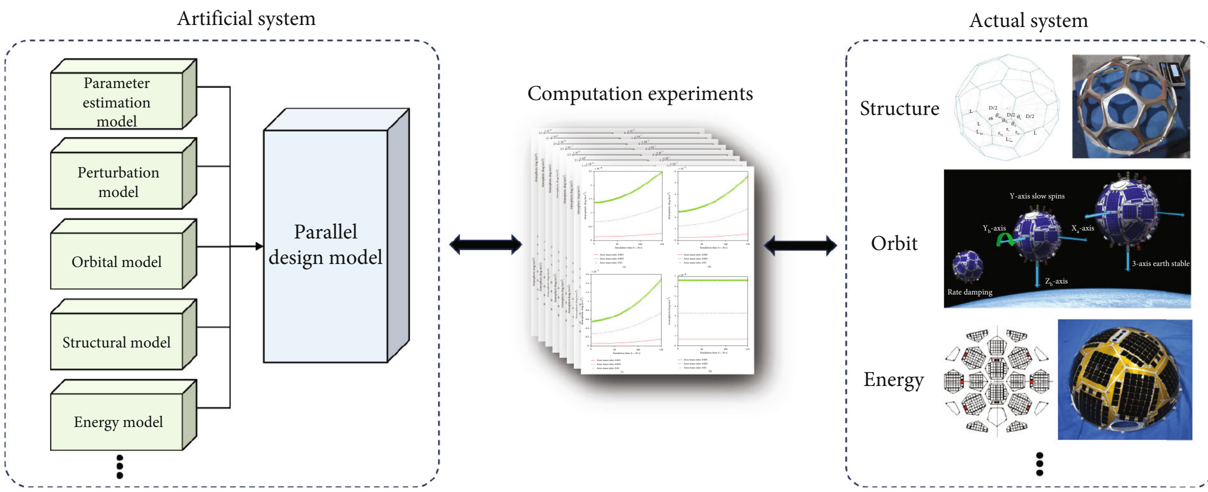

Figure 4: Q-Sat parallel design process.

Table 1: The overall mission parameters of Q-Sat.

Parameter	Value
Structure	Spherical structure
Area-to-mass ratio	$0.001\ m^2/kg$
Orbital altitude	500 km
Inclination	97.5°
Atmospheric density detection precision	$10^{-13}\ kg/m^3$
Gravity recovery precision	More than 30 orders
Orbit determination precision	Better than 10 cm
Average power	27.6 W

equipment, encompassing thermal vacuum chambers, magnetic simulation devices, vibration platforms, solar cell array simulators, and light simulators, emulates thermal, electrical, magnetic, and illumination test conditions based on the injected orbit and attitude data [40]. The actual satellite system, in turn, responds to the simulated attitude and orbit data as well as the test conditions generated by the equipment.

The measurement and control analysis software diligently monitors the real-time status of each system during satellite testing, furnishing experimental data output and quantitatively assessing system performance. Simultaneously, the experimental data is fed back to the simulation flight software to refine the artificial models and explore the influence of uncertain factors on the satellite via perturbation analysis. Through this parallel testing paradigm, the artificial systems and the actual systems evolve in parallel, fostering their mutual growth.

3.4. Parallel Operation. During the operational phase of Q-Sat in orbit, an operational system parallel to that of the actual satellite is established, as illustrated in the diagram below. Throughout this phase, a substantial amount of data, including data of satellite status and on-orbit scientific data, is transmitted by the satellite. The measurement and control analysis software processes and interprets the data of satellite status, which is then shared with the simulation flight software, allowing for parallel operation within the artificial systems. The artificial systems analyze the operation of the satellite on-orbit based on prior models and the actual data of status, while also evaluating the potential impacts on the operation of the satellite due to forecasts of solar wind and geomagnetic activity.

The scientific data from the satellite is subjected to data quality assessment by the artificial systems, which is then input into the inversion calculation model to determine long-wavelength gravity field and atmospheric density. The dynamic model is updated based on the calculated gravity field and atmospheric density results, enhancing the accuracy of Q-Sat orbit prediction within the artificial systems. By comparing the predicted orbit with highly accurate orbit data obtained from the satellite, a backpropagation neural network is trained to predict position error covariance. Additionally, the artificial model incorporates a space debris Two-Line Elements (TLE) database, enabling orbit prediction for space debris and facilitating collision monitoring and warning for Q-Sat. The operational system for Q-Sat is shown in Figure 7.

Based on the analysis and evaluation results obtained from the artificial systems, various operations such as attitude control, fault handling, parameter updates, and software upgrades are performed on the Q-Sat satellite within the real system. Concurrently, a comparative analysis between on-orbit data and ground test data is conducted to identify any disparities, leading to adjustments in the relevant parameters of the artificial systems' prior model. This ensures an improved reflection of the actual on-orbit operations of Q-Sat within the artificial systems. Through the establishment of the parallel operational system, both the real Q-Sat system and the artificial systems progress and develop in parallel.

4. Results and Discussion

One example of the applications of Q-Sat parallel systems is to analyze and process in-orbit satellite data, aiming to refine

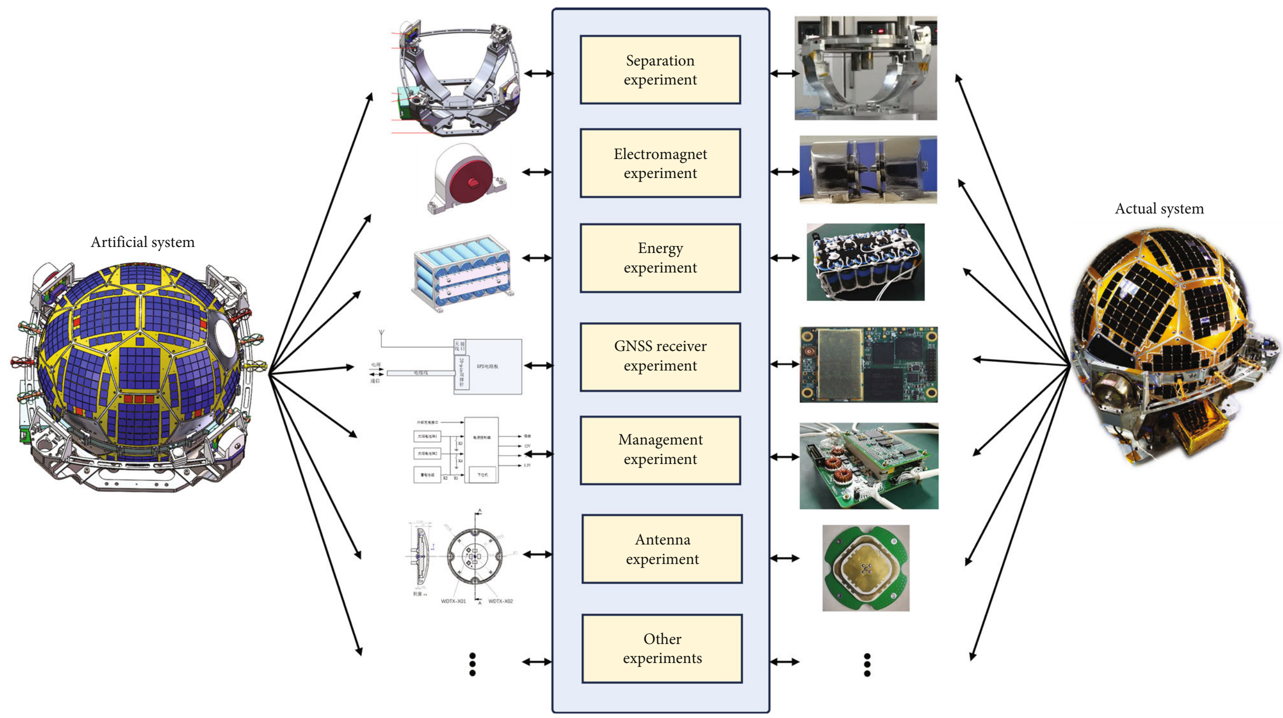

Figure 5: Q-Sat subsystem parallel development process.

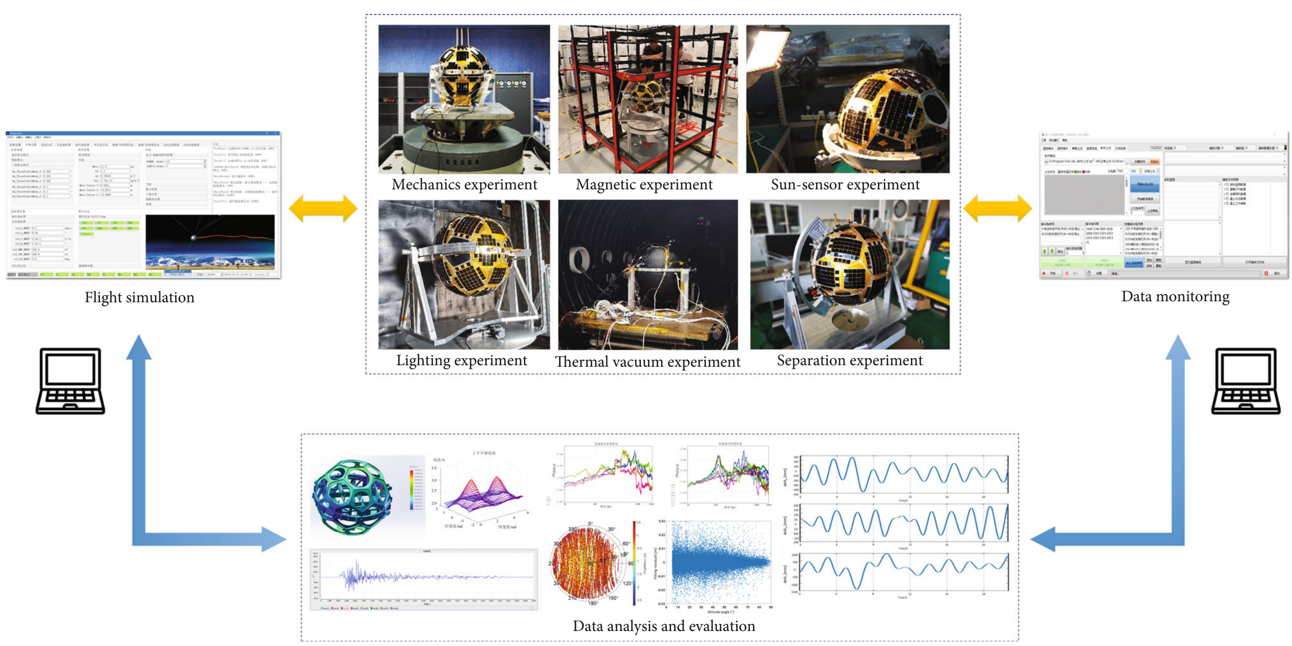

Figure 6: Q-Sat integrated parallel testing system.

the models within the artificial systems and improve the accuracy of orbit prediction and collision warning in the actual systems. The model parameters within the artificial systems are adjusted using high-precision centimeter-level orbital data from the real Q-Sat system [41, 42]. A five-day period, from January 11th to 15th, 2022, is selected, with each 24-hour orbit serving as an adjustment unit. The Jacchia-Roberts atmospheric model within the artificial systems is optimized using the dynamic inversion method, resulting in the correction factors l presented in Table 2. The corrected atmospheric density on the Q-Sat orbit was calculated and modeled for comparison with the results generated by NRLMSISE-00, as depicted in Figure 8. The accuracy of the orbit prediction model within the artificial systems is validated by comparing the forecast results for the subsequent 24 hours of the Q-Sat orbit with the precise

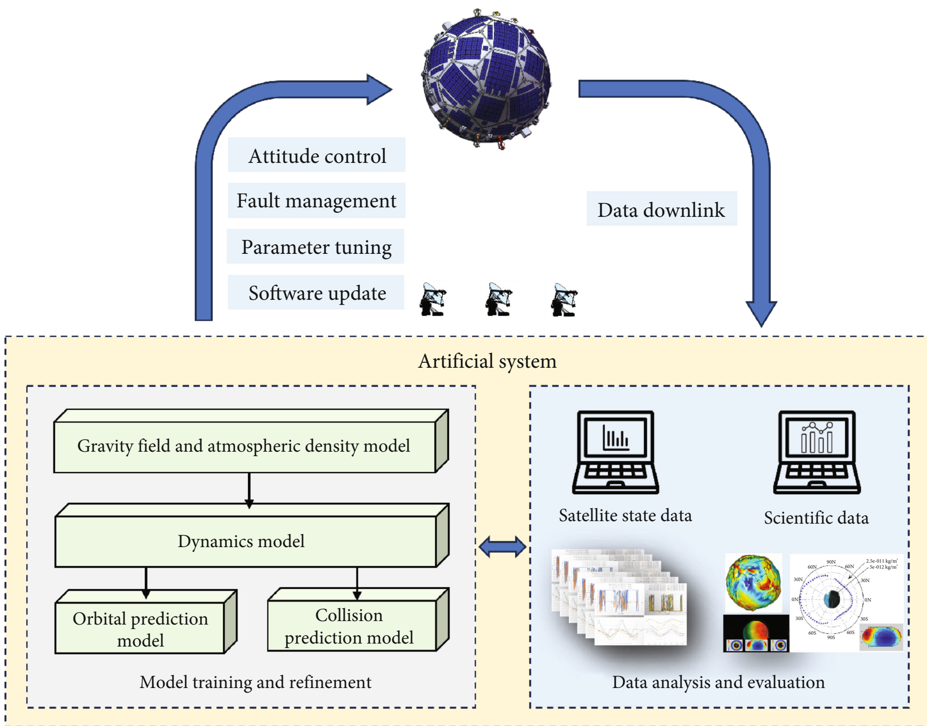

Figure 7: Q-Sat parallel operation process.

Table 2: Modified l based on daily data from January 11 to 15.

Date	Parameters to be modified in Eq. (5)				
	l_1	l_2	l_3	l_4	l_5
Jan 11th	4.6254×10^3	0.2341	1.5792×10^{-3}	-1.2525×10^{-6}	2.4627×10^{-10}
Jan 12th	5.3663×10^3	0.2341	1.5792×10^{-3}	-1.2525×10^{-6}	2.4627×10^{-10}
Jan 13th	5.1256×10^3	0.2341	1.5792×10^{-3}	-1.2525×10^{-6}	2.4627×10^{-10}
Jan 14th	4.7526×10^3	0.2341	1.5792×10^{-3}	-1.2525×10^{-6}	2.4627×10^{-10}
Jan 25th	5.2134×10^3	0.2341	1.5792×10^{-3}	-1.2525×10^{-6}	2.4627×10^{-10}

orbital data from the real system. Utilizing the improved Jacchia-Roberts model, the 24-hour forecast position error is reduced by approximately 65 meters compared to the NRLMSISE-00 model. Moreover, the optimization of the original Jacchia-Roberts model leads to an average 24-hour prediction accuracy improvement of approximately 170 meters within a 14-day period.

Another example involves Q-Sat, which, due to its attitude maneuvers in actual space, may experience insufficient numbers of navigation satellites observed by the GNSS receiver antennas, thereby affecting the continuity of the onboard GNSS receiver positioning. To address this issue, the initial artificial systems adopted an orbital propagation method to supplement the missing data. However, due to the dynamic changes in the atmospheric environment where low Earth orbit satellites operate, relying solely on orbital propagation yields low accuracy, impacting the precision of subsequent inversion calculations for Q-Sat. Utilizing the ACP-based space systems, high-precision orbit determination data measured before and after the missing orbit of Q-Sat were used to modify the atmospheric drag coefficient within the artificial systems. The modified dynamic model was able to minimize the discrepancy between the artificial systems and the real system in the missing orbit data segment, enhancing the accuracy of orbit propagation.

To compare the improvement in accuracy before and after the correction of the artificial system model, we selected continuous precise orbital data for 12 days, artificially creating missing data by extracting 1.5 hours daily as a baseline. By comparing the orbital compensation errors of the artificial system before and after correction, we can analyze the accuracy change. Taking the data from day of year (DOY) 259-270 in 2020 as an example, a comparison was made between the original artificial systems and the artificial systems modified based on real system data for the 1.5-hour missing orbit propagation error, as shown in Figure 9 and Table 3. The black curve represents the average root mean square (RMS) error of orbital propagation per day based on the original artificial systems. The red, green, and blue curves represent the propagation errors modified using real

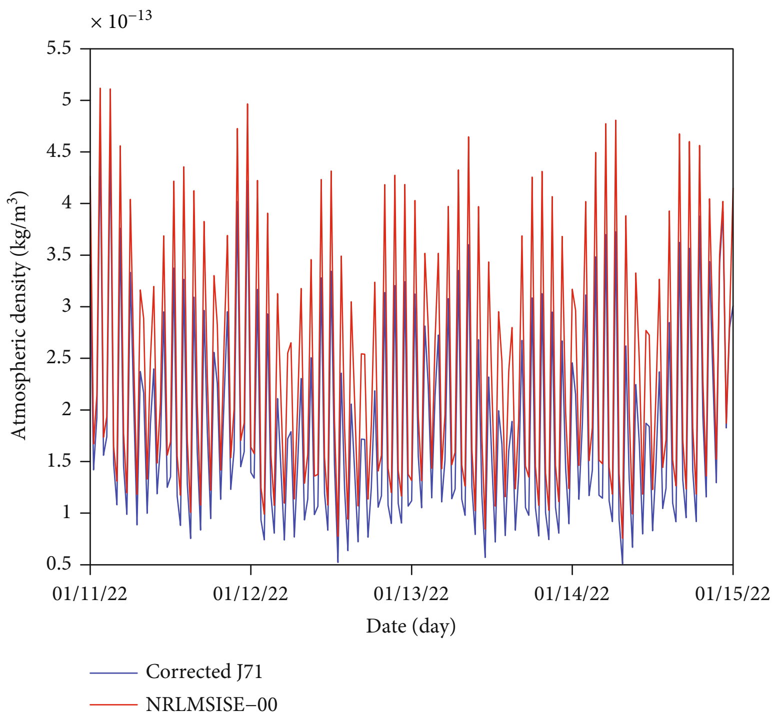

Figure 8: Atmospheric densities from different models.

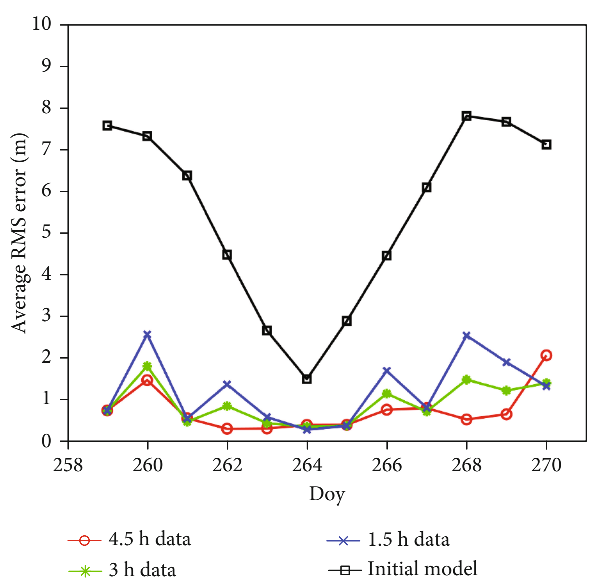

Figure 9: Comparison of orbit propagation average RMS error.

Table 3: Data of orbit propagation average RMS error.

DOY	Average RMS error (m)			
	Initial	1.5 h	3 h	4 h
259	7.5748	0.7400	0.7372	0.7452
260	7.3214	2.5693	1.8051	1.4724
261	6.3809	0.5543	0.4731	0.5575
262	4.4810	1.3697	0.8512	0.3074
263	2.6610	0.5866	0.4423	0.3132
264	1.4966	0.2842	0.3519	0.3983
265	2.8898	0.3763	0.3792	0.4011
266	4.4589	1.6944	1.1487	0.7630
267	6.0919	0.8121	0.7190	0.8025
268	7.8049	2.5425	1.4849	0.5297
269	7.6635	1.9015	1.2207	0.6542
270	7.1225	1.3235	1.3996	2.0675

orbital data 4.5 hours before and after, 3 hours, and 1.5 hours, respectively, around the missing orbit. The results indicate that the unmodified artificial systems' average RMS error for orbital propagation was 5.496 m, while the modified artificial systems' average RMS error was reduced to 0.689 m, improving accuracy by 86.5%. This dynamic-based method for extending the missing orbit data, on one hand, reduced the discrepancies between the artificial and actual systems and, on the other hand, addressed the accuracy decline caused by divergence, thereby better supporting Q-Sat missions.

Furthermore, using high-precision orbital data from the real Q-Sat system and TLE data from space debris, the position error covariance prediction BP neural network within the artificial systems is trained [43]. Taking the space debris with a NORAD ID of 49863 as an example, the trained prediction results are illustrated in Figure 10, along with the relationship between relative distance and collision probability, as shown in Figure 11. This method significantly enhances the fidelity of Q-Sat collision prediction. It is evident that the ACP-based parallel systems facilitate parallel

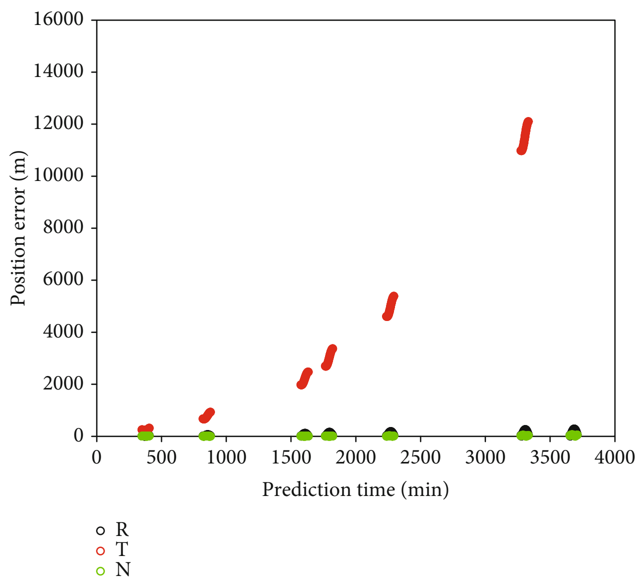

FIGURE 10: Prediction error distribution of space debris.

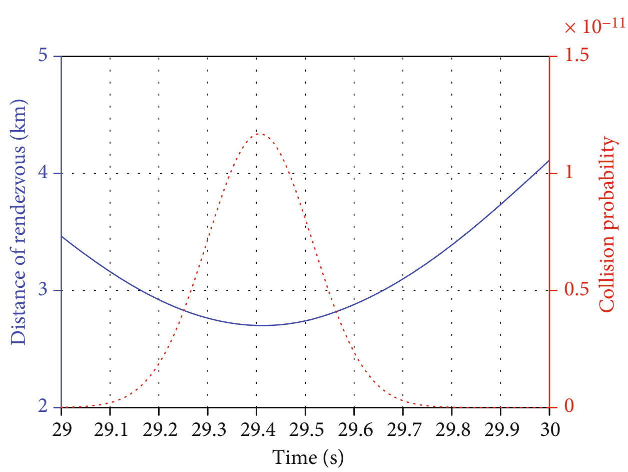

FIGURE 11: Graph of relative distance and collision probability.

enhancement and development between the real Q-Sat system and the artificial systems.

5. Future Perspective

With the enhancement of computational power and improvement of data acquisition techniques, the future parallel space systems will play a greater role and find widespread applications in various stages of the space system life cycle, including system design, production, integration, testing, and operation. The development of future parallel space systems will exhibit trends towards digitization, integration, and adaptability.

5.1. Digitization. Digitization forms the foundation of parallel space systems, where the physical systems within space systems are accurately transformed into information space. To achieve this, mathematical models enabling integrated multiphysics, multiscale, probabilistic simulations specific to space systems are required as the basis for simulation and replication. In the future, fully digital space systems will be realized through software implementation, rather than just hardware entities. Space parallel systems based on multidisciplinary digital models will offer advantages such as convenience, flexibility, and low cost, finding extensive applications in every aspect of future aerospace system manufacturing and utilization. This digital development will enable us to simulate and predict the behaviors of space systems more accurately, enhancing our understanding and control capabilities over space systems.

5.2. Integration. Integration is integral to parallel space systems. Instead of the traditional approach with on-orbit satellites as the primary focus and simulation systems as auxiliary, parallel operation treats both as a single entity, collectively accomplishing missions. Future real space systems and artificial space systems will compare and analyze behaviors of each other autonomously, estimate their respective future states, learn from each other's strengths, and adjust their management and control methods. Parallel systems will be conveniently and flexibly applied across various stages of the space system's life cycle, including design, production, integration, testing, and operation, achieving integrated design and parallel operation of real and artificial systems.

5.3. Adaptability. In future space missions, particularly those of long duration and complexity, parallel space systems need to self-adjust and optimize based on constantly changing environments and requirements. This necessitates stronger adaptability within the systems. To achieve this, parallel space systems should incorporate technologies such as artificial intelligence and machine learning, enabling the systems to learn and evolve from historical data and real-time feedback, automatically adapting to various circumstances. During parallel operation, simulation systems not only closely interact with real systems but also compare and analyze in real time, self-adjusting based on the results to optimize performance and efficiency. Future space systems will benefit from this adaptability development, further enhancing the overall robustness and reliability of the system.

Digitization, integration, and adaptability will shape the future of parallel space systems, facilitating mutual learning and optimization between artificial and real systems. This will optimize and streamline the design and operation of space systems, better supporting space missions, enhancing our understanding and control capabilities over complex space environments, and opening up broader pathways for human space exploration.

6. Conclusion

The present study establishes a parallel space system architecture based on ACP, proposing the concept of parallel design, development, and operation for different stages of space systems. This research explores a novel architecture for space systems. By creating artificial systems based on real space systems and conducting computational experiments, an ample amount of sample data is generated. This not only improves the model of the artificial systems but also optimizes the real system, facilitating parallel advancement between the two. The design, development, and operation processes of Q-Sat based on ACP are presented, along with an analysis of the advantages of parallel space systems. The computation and modeling of corrected atmospheric density along the Q-Sat orbit, utilizing the enhanced Jacchia-Roberts model, resulted in a reduction of approximately 65 m in the 24-hour forecast position error compared to the NRLMSISE-00 model. Furthermore, optimization of the original Jacchia-Roberts model led to an improvement of about 170 m in the average 24-hour prediction accuracy within a 14-day span. Addressing the divergences between the artificial systems and the parallel systems, the ACP-based space systems can effectively reduce the divergences between system models. The accuracy of the corrected orbital propagation improved by 86.5%. These substantiate the notion that ACP-based space systems can facilitate parallel development between artificial systems and real systems. The future outlook indicates a trend towards more efficient and reliable space systems through digitization, integration, and adaptability. This research provides valuable insights into the potential of parallel space systems and sets the stage for further advancements in the field.

Data Availability

The Q-Sat data used to support the findings of this study may be released upon application to the author, who can be contacted at cyk19@mails.tsinghua.edu.cn.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

This work was supported by the National Natural Science Foundation of China under Grant No. U20B2056 and National Key Research and Development Program of China (No. 2022YFC2204204 and No. 2023YFC2205601).

References

[1] V. L. Pisacane, *Fundamentals of Space Systems*, Oxford University, New York, NY, 2005.

[2] Z. Jiang, W. Li, X. Wang, and B. Liang, "A Leo satellite handover strategy based on graph and multiobjective multiagent path finding," *International Journal of Aerospace Engineering*, vol. 2023, Article ID 1111557, 16 pages, 2023.

[3] J. C. McDowell, "The low Earth orbit satellite population and impacts of the SpaceX Starlink constellation," *The Astrophysical Journal Letters*, vol. 892, no. 2, p. L36, 2020.

[4] H. Liao, J. Xie, X. Zhou et al., "Compound attitude maneuver and collision avoiding control for a novel noncontact close-proximity formation satellite architecture," *International Journal of Aerospace Engineering*, vol. 2022, Article ID 2606233, 11 pages, 2022.

[5] Y. Xu, Y. Zhang, Z. Wang, Y. He, and L. Fan, "Self-organizing control of mega constellations for continuous Earth observation," *Remote Sensing*, vol. 14, no. 22, p. 5896, 2022.

[6] H. Liu, Z. Chen, X. Wang, and Z. Sun, "Optimal formation control for multiple rotation-translation coupled satellites using reinforcement learning," *Acta Astronautica*, vol. 204, pp. 583–590, 2023.

[7] G. Horneck, "Space Environment," in *Encyclopedia of Astrobiology*, M. Gargaud, Ed., pp. 153–198, Springer, Berlin, Heidelberg, 2015.

[8] L. Zhao, C. Yuan, X. Li, and J. He, "Multiple spacecraft formation flying control around artificial equilibrium point using propellantless approach," *International Journal of Aerospace Engineering*, vol. 2022, Article ID 8719645, 26 pages, 2022.

[9] L. Yonglin, W. Weiping, L. Qun, and Z. Yifan, "A transformation model from DEVS to SMP2 based on MDA," *Simulation Modelling Practice and Theory*, vol. 17, no. 10, pp. 1690–1709, 2009.

[10] B. Hu, H. Chen, L. Han, and H. Yu, "Research and ground verification of the force compliance control method for space station manipulator," *International Journal of Aerospace Engineering*, vol. 2020, Article ID 8896610, 17 pages, 2020.

[11] C. S. Lim and A. Jain, "Dshell++: a component based, reusable space system simulation framework," in *2009 third IEEE international conference on space Mission challenges for information technology*, Pasadena, CA, USA, July 2009.

[12] A. Madni, C. Madni, and S. Lucero, "Leveraging digital twin technology in model-based systems engineering," *Systems*, vol. 7, no. 1, p. 7, 2019.

[13] S. Liu, Y. Lu, X. Shen, and J. Bao, "A digital thread-driven distributed collaboration mechanism between digital twin manufacturing units," *Journal of Manufacturing Systems*, vol. 68, pp. 145–159, 2023.

[14] D. J. L. Siedlak, O. J. Pinon, P. R. Schlais, T. M. Schmidt, and D. N. Mavris, "A digital thread approach to support manufacturing-influenced conceptual aircraft design," *Research in Engineering Design*, vol. 29, no. 2, pp. 285–308, 2018.

[15] Q. Zhang, S. Zheng, C. Yu, Q. Wang, and Y. Ke, "Digital thread-based modeling of digital twin framework for the aircraft assembly system," *Journal of Manufacturing Systems*, vol. 65, pp. 406–420, 2022.

[16] N. Eskue, "Digital thread roadmap for manufacturing and health monitoring the life cycle of composite aerospace components," *Aerospace*, vol. 10, no. 2, p. 146, 2023.

[17] L. Zhao, Z. Wu, L. Cheng, and G. Zhan, "Preliminary discussion on the application of digital thread in the model-based spacecraft development," in *Lecture Notes in Electrical Engineering*, pp. 606–613, Springer, Singapore, 2023.

[18] F.-Y. Wang, "Parallel control and management for intelligent transportation systems: concepts, architectures, and applications," *IEEE Transactions on Intelligent Transportation Systems*, vol. 11, no. 3, pp. 630–638, 2010.

[19] F.-Y. Wang, "Toward a paradigm shift in social computing: the ACP approach," *IEEE Intelligent Systems*, vol. 22, no. 5, pp. 65–67, 2007.

[20] X. Li, K. Wang, X. Gu, F. Deng, and F.-Y. Wang, "ParallelEye pipeline: an effective method to synthesize images for improving the visual intelligence of intelligent vehicles," *IEEE Transactions on Systems, Man, and Cybernetics: Systems*, vol. 53, no. 9, pp. 5545–5556, 2023.

[21] J. Chen, Y. Zhang, S. Teng, Y. Chen, H. Zhang, and F.-Y. Wang, “ACP-based energy-efficient schemes for sustainable intelligent transportation systems,” *IEEE Transactions on Intelligent Vehicles*, vol. 8, no. 5, pp. 3224–3227, 2023.

[22] X. Wang, X. Cheng, J. Lu, O. Kwan, S. Li, and Z. Ping, “Metaverses-based parallel oil fields in CPSS: a framework and methodology,” *IEEE Transactions on Systems, Man, and Cybernetics: Systems*, vol. 53, no. 4, pp. 2138–2147, 2023.

[23] J. Han, M. Yang, X. Chen et al., “Paradefender: a scenario-driven parallel system for defending metaverses,” *IEEE Transactions on Systems, Man, and Cybernetics: Systems*, vol. 53, no. 4, pp. 2118–2127, 2023.

[24] X. Wang, J. Yang, Y. Wang et al., “Steps toward industry 5.0: building “6s” parallel industries with cyber-physical-social intelligence,” *IEEE/CAA Journal of Automatica Sinica*, vol. 10, no. 8, pp. 1692–1703, 2023.

[25] J. Wang, X. Wang, Y. Tian, Y. Wang, J. Niu, and O. Kwan, “Parallel training: an ACP-based training framework for iterative learning in uncertain driving spaces,” *IEEE Transactions on Intelligent Vehicles*, vol. 8, no. 4, pp. 2832–2841, 2023.

[26] J. Lu, Q. Wei, T. Zhou, Z. Wang, and F.-Y. Wang, “Event-triggered near-optimal control for unknown discrete-time nonlinear systems using parallel control,” *IEEE Transactions on Cybernetics*, vol. 53, no. 3, pp. 1890–1904, 2023.

[27] C. Guo, Y. Dou, T. Bai, X. Dai, C. Wang, and Y. Wen, “ArtVerse: a paradigm for parallel human–machine collaborative painting creation in metaverses,” *IEEE Transactions on Systems, Man, and Cybernetics: Systems*, vol. 53, no. 4, pp. 2200–2208, 2023.

[28] M. Kang and F.-Y. Wang, “From parallel plants to smart plants: intelligent control and management for plant growth,” *IEEE/CAA Journal of Automatica Sinica*, vol. 4, no. 2, pp. 161–166, 2017.

[29] M. Fan, M. Kang, X. Wang, J. Hua, C. He, and F.-Y. Wang, “Parallel crop planning based on price forecast,” *International Journal of Intelligent Systems*, vol. 37, no. 8, pp. 4772–4793, 2022.

[30] A. Cerrone, J. Hochhalter, G. Heber, and A. Ingraffea, “On the effects of modeling as-manufactured geometry: toward digital twin,” *International Journal of Aerospace Engineering*, vol. 2014, Article ID 439278, 10 pages, 2014.

[31] W. Zhaokui, H. Dapeng, L. Boxin et al., “Q-Sat for atmosphere and gravity field detection: design, mission and preliminary results,” *Acta Astronautica*, vol. 198, pp. 521–530, 2022.

[32] Z. Zhao, Z. Wang, and Y. Zhang, “A spherical micro satellite design and detection method for upper atmospheric density estimation,” *International Journal of Aerospace Engineering*, vol. 2019, Article ID 1758956, 15 pages, 2019.

[33] S. Jin, T. van Dam, and S. Wdowinski, “Observing and understanding the Earth system variations from space geodesy,” *Journal of Geodynamics*, vol. 72, pp. 1–10, 2013.

[34] O. Montenbruck, E. Gill, and F. H. Lutze, “Satellite orbits: models, methods, and applications,” *Applied Mechanics Reviews*, vol. 55, no. 2, pp. B27–B28, 2002.

[35] C. E. Roberts Jr., “An analytic model for upper atmosphere densities based upon Jacchia’s 1970 models,” *Celestial Mechanics*, vol. 4, no. 3–4, pp. 368–377, 1971.

[36] H. Yunhan, W. Zhaokui, and Z. Yulin, “The electromagnetic separation system for the small spherical satellite Q-Sat,” *Acta Astronautica*, vol. 184, pp. 180–192, 2021.

[37] Y. Cai and Z. Wang, “GNSS receiver for Q-SAT and its analysis of precise orbit determination,” *Acta Astronautica*, vol. 200, pp. 357–370, 2022.

[38] Y. Cai, Y. Li, and Z. Wang, “Real-time high-precision baseline measurement of satellite formation flying based on GNSS,” *Advances in Space Research*, 2024.

[39] Y. He, Z. Wang, and Y. Zhang, “The design, test and application on the satellite separation system of space power supply based on graphene supercapacitors,” *Acta Astronautica*, vol. 186, pp. 259–268, 2021.

[40] Y. He, B. Li, Z. Wang, and Y. Zhang, “Thermal design and verification of spherical scientific satellite Q-sat,” *International Journal of Aerospace Engineering*, vol. 2021, Article ID 9961432, 11 pages, 2021.

[41] K. Shao, C. Wei, D. Gu et al., “Tsinghua scientific satellite precise orbit determination using onboard GNSS observations with antenna center modeling,” *Remote Sensing*, vol. 14, no. 10, p. 2479, 2022.

[42] Z. Wang, Y. Zhang, G. Wen et al., “Atmospheric density model optimization and spacecraft orbit prediction improvements based on Q-Sat orbit data,” 2021, https://arxiv.org/abs/2112.03113.

[43] H. Pu, W. Guangwei, C. Yingkai, and W. Zhaokui, “Reduction of space debris collision prediction uncertainty based on Q-Sat precise orbit,” *Space: Science & Technology*, vol. 3, Article ID 0005, 2023.