Journal of Reliability
Science and
Engineering

PAPER • OPEN ACCESS

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To cite this article: Mao Li *et al* 2025 *J. Reliab. Sci. Eng.* **1** 044001

OPEN ACCESS
IOP Publishing | ISECAEP
Journal of Reliability Science and Engineering
J. Reliab. Sci. Eng. **1** (2025) 044001 (9pp)
https://doi.org/10.1088/3050-2454/ae0b71

Reliability design and management in CZ-5 launch vehicle electrical system

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Received 2 July 2025, revised 23 August 2025
Accepted for publication 23 September 2025
Published 17 October 2025

Abstract

The CZ-5 series launch vehicle holds a pivotal position as one of the key enablers and milestones propelling China toward a powerful force in spaceflight (Li *et al* 2017 *Missiles Space Veh.* 1–5). Among its integral components, the electrical system has undergone extensive reliability design and verification exercises. Initially, this document presents an overview of the fundamental characteristics of the CZ-5 rocket and the composition of its electrical system. It further reviews the system-level redundancy and fault-tolerant designs, alongside the safety designs included within the electrical system's reliability framework during potential fault scenarios. Moreover, it consolidates the elements of the verification elements. Implementing systematic redundancy strategies at the system level, combined with comprehensive full-link verification, significantly enhances the rocket's reliability. This approach embodies the core principles of reliability-driven engineering throughout the development life cycle.

Keywords: rocket, electrical system, reliability, practice

1. Introduction

The technical maturity of launch vehicles serves as a critical indicator of a nation's space access capability. It determines the scale and sophistication of space activities, while also forming the foundational prerequisite for space exploration, utilization, and development. The launch vehicle is mainly composed of an electrical system, a propulsion system, and a structure system. The electrical system is the mission-critical control architecture of the launch vehicle, it is mainly used to accomplish the functions of rocket flight control, parameter measurement, data communication, and fault detection, which can be divided into control, measurement, energy, communication, fault detection modules.

Launch vehicles represent complex systems characterized by ultra-complex architectures, exorbitant development costs, operationally extreme environments, non-recoverable failure modes, and catastrophic mission consequence of mission failure. Every year, however, there are failures in rocket launches. For example, China's Long March has carried out more than 500 space launches so far, with a success rate of about 96%. The failure of a rocket launch means huge economic losses and may even represent the death of the pioneers of human exploration in space. Therefore, the reliability research of launch vehicles needs to be carried out throughout its life cycle, reliability is the most critical metric for launch vehicles [1].

The CZ-5 is the first large cryogenic launch vehicle developed in the new century under the leadership of CNSA, it mainly undertakes the mission of lunar exploration, space station, and other major national projects, and is one of the important supports and prominent symbols of China's transformation from a space power to a space power [2]. As a next-generation heavy-lift launch vehicle, CZ-5 has made great

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strides in the application of new technology and the improvement of its carrying capacity. As an important part of CZ-5, the electrical system has been deeply studied in reliability and safety design, design management, system verification including reliability allocation, failure mode mitigation, and validation protocols. In this paper, the reliability working method of the CZ-5 electrical system in the development process is summarized to guide the reliability design of the electrical system of the future launch vehicle.

2. Electrical system of the CZ-5

The CZ-5 series launch vehicle adopts a modular design scheme, in which the total length of the launch vehicle is about 57 m, 5 m diameter core bundles four 3.35 m-booster, with a take-off weight of about 880t and the configuration with two and half stage, it is composed of four major systems: the structural system, the propulsion system, the electrical system, and ground launch-supporting system. During the GTO mission, the CZ-5 experienced the following key events, as shown in figure 1 [2].

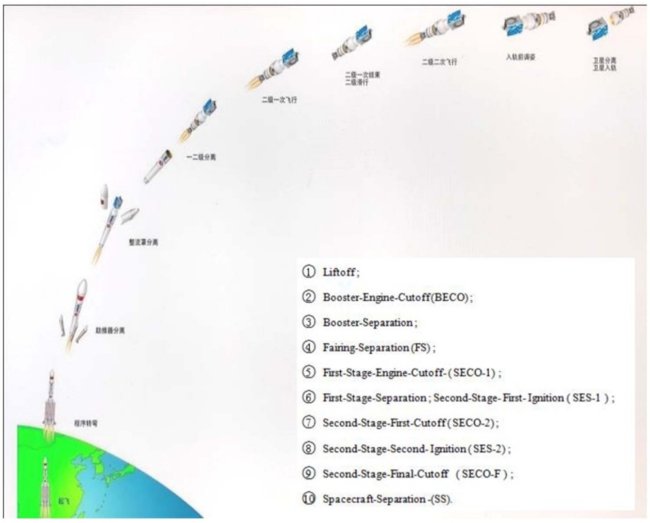


Figure 1. Flight timing sequence: describes the ten key maneuvers during the flight of the long March 5 rocket.

The electrical system of a launch vehicle is a functional system composed of electrical components, electronic devices, and software. The main function of the electrical system is to control the launch vehicle to send the payload into the predetermined orbit, to ensure the accuracy of the orbit, to implement the attitude control of the launch vehicle, to ensure the flight stability under various conditions. The telemetry parameters of the rocket are measured, transmitted, and processed, and the external trajectory monitoring of the rocket is measured and controlled. Comprising the control system and the measurement system, the electrical system's functional modules include the following parts [3], as shown in figure 2.

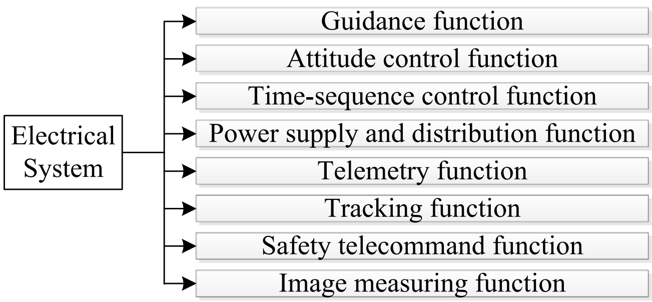


Figure 2. Frame of the electrical system: the diagram illustrates the eight major functional modules of the launch vehicle's electrical system.

The power supply and distribution function primarily provides energy to electrical equipment during rocket flight. The guidance, attitude, and timing control functions are responsible for navigation computation, guidance control, attitude control, and timing control during flight. The telemetry function acquires and processes various flight parameters in real time. The tracking function monitors the rocket's flight path. The image measurement function captures and processes video data from critical onboard components. The safety telecommand function activates the rocket's self-destruct mechanism in the event of a critical failure during flight.

3. Reliability design of the electrical system

3.1. Reliability design methods for electrical systems

Reliability is the ability of a product to perform specified functions under specified conditions and within a specified time duration. This ability is a probabilistic characteristic of a product. Reliability work plays a decisive role in the success or failure of the rocket, and at the same time, through decades of space practice experience, has been distilled into 'the threefold principle: reliability-by-design, reliability-by-manufacturing, reliability-by-management the valuable understanding [4, 5].

At the beginning of the development of the CZ-5 rocket, a reliability design index 0.98 was stipulated and implemented in layers. As an important part of a launch vehicle, electrical system design reliability includes design, analysis, testing and evaluation. Reliability design plays a decisive role in the reliability level of products. In the process of development, many reliability design methods are used, such as simplified design, fault-tolerant design, redundancy design, derating design, etc [6].

Based on the accumulated experience from previous rocket development programs, electrical system reliability design criteria have been formulated to guide the launch vehicle system development, as detailed below:

1) Advanced technology adoption criteria: implement cutting-edge circuit design technologies such as MIL-STD-1553B data bus to enhance system performance;

2) System simplification criteria: adopt an integrated design approach for electrical systems, streamlining system interfaces and reducing device complexity to improve reliability;
3) Redundancy enhancement criteria: implement redundant configurations for mission-critical functions including bus communication, flight control, and servo actuation to ensure system fault tolerance [7]:
4) Design margin optimization criteria: maintain sufficient design margins for critical functions to accommodate operational deviations during flight trajectories;
5) Fault isolation capability criteria: establish real-time fault containment mechanisms to isolate anomalies while maintaining nominal flight operations;
6) End-to-end validation criteria: conduct comprehensive validation of error-prone functions through complete signal chain verification from sensor input to control output.

Fault-tolerant design generally refers to the process of system project design, considering potential failure modes, by implementing hardware/software- based fault detection and recovery mechanisms to maintain the normal operation of the system. Fully considering and adopting fault-tolerant architecture can obviously improve the reliability of the system or task, otherwise it may be helpless against fault. In order to eliminate the effect of system or product failure, redundant design usually invests more resources than conventional design, in exchange for higher system reliability and security [8]. Additional hardware equipment is the most important measure of redundancy technology, with more than two sets of equipment parallel work, as long as one set of equipment work properly, the task will not fail. For example, the design concepts of redundancy and fault tolerance are adopted for flight control and communication of rockets.

3.2. *System redundant and re-configurable architecture*

The development of the CZ-5 rocket has led to the wide application of system-level redundancy technology based on MIL-STD-1553B data bus in China's new generation launch vehicle, resulting in significant improvement in system reliability and the ability to deal with a variety of single-point failure modes in flight significantly improved [9].

In the system design, we have devised and implemented a comprehensive system-level redundant reconfiguration control strategy that incorporates a hybrid 'Ring Laser Gyroscope (RLG) and a Fiber-Optic Gyroscope (FOG) Inertial Measurement Units (IMUs)' configuration along with a multi-rate gyroscope setup, as illustrated in the subsequent diagram. To guarantee redundancy across every component of the control system, we leverage advanced techniques such as the voting switch and reconfiguration capabilities of the rocket bus controller (BC), the triple redundant reconfiguration of IMUs, the reconfiguration control of rate gyroscope data and angular velocity information, the reprocessing of apparent acceleration data from strap down accelerometers and IMUs, and employing three independent redundant servo subsystems.

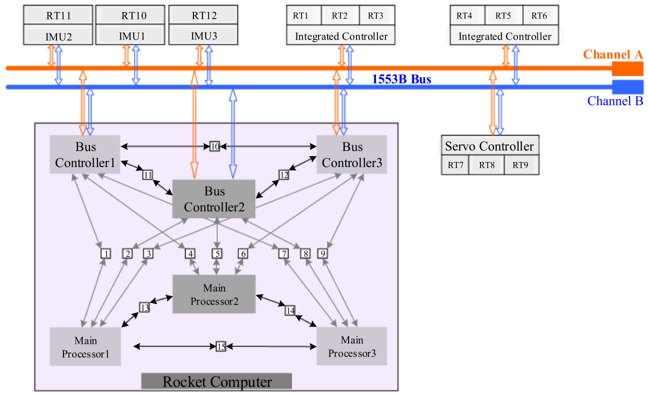


Figure 3. Digital reconfigurable architecture based on the 1553B bus: the diagram depicts the architecture of the MIL-STD−1553B bus in the electrical system, illustrating the connection methods between devices and the bus. Key equipment operates in a triple-redundant configuration, with the bus divided into Channel A and Channel B.

These innovations significantly boost the overall reliability of the rocket while enhancing its control system's ability to adapt to various faults in a holistic manner. This results in a paradigm shift from the conventional mode of fault absorption to a more proactive approach involving fault diagnosis, isolation, and real-time reconfiguration [10].

The 1553B data bus, which is highly reliable and double-redundant, is used to connect all intelligent devices through a double-channel 1553B bus, and the rocket computer acts as the BC, responsible for bus-data flow management and scheduling of the control system. The BC is designed with triple modular redundancy (TMR) and *e* is equipped with three 1553B Bus Interface Units (BIU) to realize the triple-redundancy BC. The Triple Redundancy BC works as a hot backup, which is used to realize system-level redundancy fault-tolerant control and fault isolation. When the BC communicates with each RT station in the bus network, it first communicates via bus 'channel A' by default, and when the communication with one RT station is not successful, the bus channel of the RT is switched to B; if communication is successful on B, the communication with the RT is maintained on B, whether or not A is restored to normal; when communication with B is not successful, then the bus is switched to A, as shown in figure 3.

In the system information interaction, all input and output data are redundancy voting mechanisms (2-out-of-3 voting). According to the allocation control strategy, the fault information is isolated to realize the dynamic reconfiguration of the system. The rocket computer collects the information of three redundant IMUs via the MIL-STD-1553B bus. After information redundancy calculation and decision, the control results are given to the servo system. The TMR architecture is also adopted in the servo system. The servo controller receives the three-redundancy digital control instructions on the 1553B bus, at the same time, the servo controller collects the linear displacement signal of the three redundant displacement sensors of the servo mechanism, and executes a majority voting algorithm and the data closed-loop control

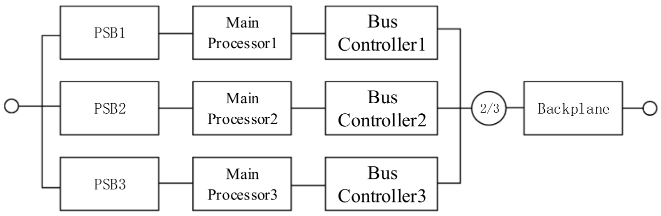


Figure 4. Flight reliability block diagram of the onboard computer: in the diagram, PSB refers to the power supply module of the equipment, the main processor is the computing module, the bus controller is the bus controller, and the backplane is the equipment backplane. All critical modules adopt a triple redundancy design.

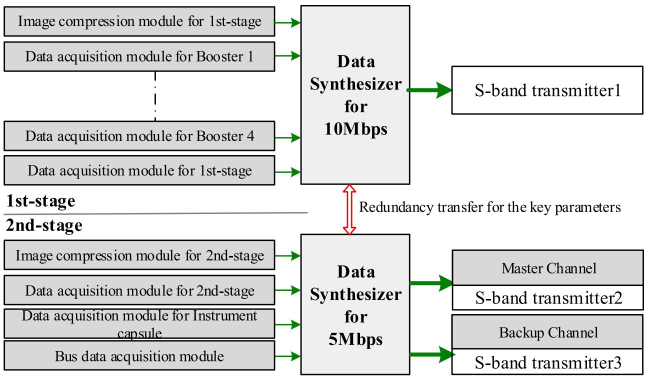


Figure 5. The diagram of CZ-5 telemetry system.

algorithm, where the action instructions are output to the three redundant pre-stages of the servo valve and subjected to 2-out-of-3 voting, thus the first-degree fault of the absorption redundant channel can be resolved.

Through system-level redundancy design for critical equipment, the flight reliability of the system can be effectively enhanced. This enables the CZ-5 launch vehicle to achieve a reliability of 0.98, while commercial rockets of similar class internationally typically exhibit reliability metrics above 0.95. The control system of CZ-5 operates for approximately 2600 s during flight, achieving a flight reliability of 0.998. This makes it the most reliable operational launch vehicle currently in active service within China's rocket fleet.

For the core equipment of the control system, the onboard computer consists of a PSB power supply module, CPU module, BC module, and backplane circuitry. All critical modules are designed with triple redundancy. Its reliability block diagram model is established based on the product design scheme and the working principle, as shown in figure 4. Its flight reliability can reach 0.999 994 [11, 12].

3.3. High speed dual-point FM telemetry technology

The telemetry parameters of the CZ-5 are over 5500, including 3000 bus parameters and 2500 non-bus parameters. The total telemetry capacity of the CZ-5 is increased from 4 Mbps (megabits per second) to 15 Mbps, with an unprecedented data volume, so a new design concept is needed to satisfy the reliable transmission of onboard data. In order to make full use of the telemetry and control resources, the measurement system adopts the high bit rate and dual-frequency shift keying modulation telemetry scheme as follows [13]:

1) 10 Mbps S-band telemetry subsystem: It is installed on the core first stage of the rocket, utilizing a PCM-FM transmission system, S-band, for transmitting all telemetry parameters of the core first stage, four boosters, fairing, and 10-channel video data of the first stage and the boost engine cabin. At the same time, the redundant transmission of the key parameters of the second-level part is completed. After the booster separation, adaptive bit rate reduction is implemented by using the variable bit rate technique to complete the remaining parameters excluding booster-related parameters while maintaining downlink of dual-channel video streams of the core first stage.
2) 5 Mbps frequency: The telemetry subsystem is installed in the instrument cabin of the rocket, employing a PCM-FM modulation scheme in the S-band frequency range, which is used to transmit all second-stage telemetry parameters (e.g. temperature, pressure, vibration) and real-time image streams of the second stage and the instrument cabin. At the same time, the dual-channel spatial diversity transmission for some critical first-stage parameters (e.g. combustion chamber pressure, LOX tank temperature) in the first stage is completed.

The composition of the telemetry system is shown in figure 5, the image compression module, data acquisition and processing module, and bus data acquisition module collectively gather various onboard parameters. These parameters are transmitted to the data synthesizer for processing and compression, then relayed through the s-band transmitter to the ground receiving system. Both the first stage and second stage of the rocket are equipped with dedicated telemetry systems. Dual-frequency independent architecture can improve the reliability of the system [14]. Each frequency is responsible for the measurement of telemetry parameters, acquisition, integrated framing and modulation. In order to improve the reliability of acquiring the key parameters of the whole rocket, before the separation of the first and second stage of the rocket, the dual-frequency of the first and second stage implements hot-standby redundancy during pre-separation phase.

3.4. Fail-safe design of system

The core cryogenic stage of CZ-5 adopts high-performance hydrogen-oxygen propellants, and the burning time of the first stage is up to 480 s, which is double that of the predecessor. Therefore, the multi-engine works at the same time and the first stage works for a long time, resulting in high peak heat flow at the bottom of the rocket, which is a significant feature of CZ-5. The pulling-plug (named in Chinese TB) of the electrical system is located at the bottom of the first stage of the rocket, which is used to complete the communication, power supply and other key signal transmission before lift off. It is very important for the rocket. Through the analysis of the flight data of the rocket, it can be seen that the heat flow at the bottom

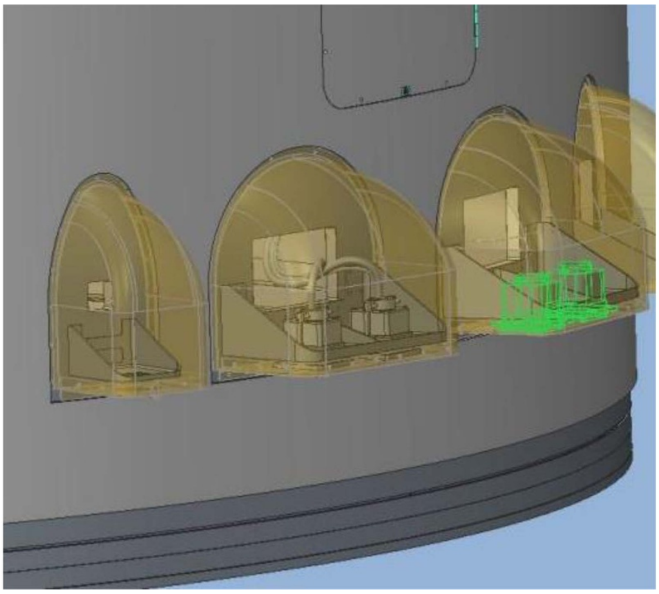
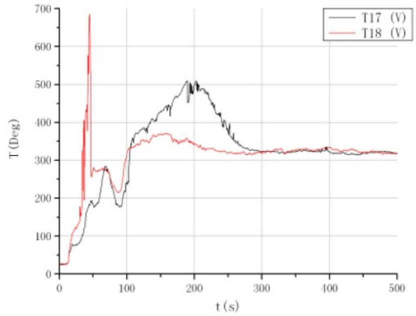
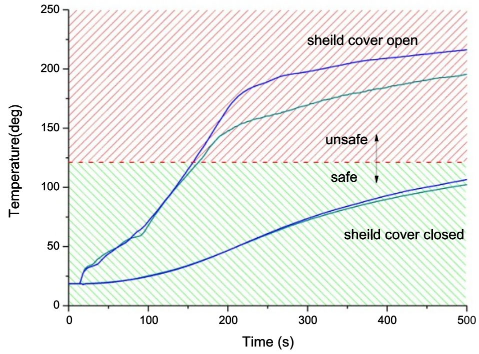


Figure 6. Protective cover of TB: the diagram depicts the use of a protective cover to safeguard the connector between the rocket and the ground.



(a) Surface temperature of TB



(b) Inner temperature of TB

Figure 7. Temperature curve of the TB: the diagram also shows the variation in temperature inside and outside the TB connector over the rocket's flight time.

of the rocket is large during the transonic flight (about 60 s–80 s after take-off), which may cause damage to the cables of the first stage aft cabin. Therefore, a protective cover is designed outside the TB, as shown in the following figure 6.

In order to find whether the protective cover of the TB is a single failure point or not, a thermal protection test of the TB was carried out. The test results show that when the rocket ignites and takes off, if the TB cover is not tightly closed, the TB is ablated under the action of the heat flow at the bottom of the rocket. This results in the solder of the TB melting and short-circuiting, in turn, it may lead to the failure of the control system in flight, which will eventually lead to the failure of the flight. The temperature curve of the TB after ignition without protection is shown in figure 7.

As shown in the diagram, after ignition, the highest surface temperature is near 500 °C on the outside of the TB, and the surface temperature of the metal shell of the TB is greater than 200 °C, which will bring about a fatal effect to the TB, and then affect the flight safety of the rocket.

To eliminate the potential risk, the system has carried out a security design, ensuring flight security, specifically including the following points:

(1) Double-layer pull-out connector is adopted in the TB, and titanium alloy is used to improve the heat resistance of the electrical connector and reduce the probability of tin melting;
(2) The cables of the control system set detachable plugs, and disconnect the detachable plugs at a proper time after receiving the take-off signal. Thus, it will not lead to the short connection of positive and negative signals in the flight process, even if the connector is melted under high and long time heat flow, as shown in figure 8.
(3) For the TB of the control system and the measurement system, the pin distribution has carried on the optimization design, mainly with two improvements. The utility model ensures that a short circuit of the positive and negative busbar cannot occur even if the plug is ablated. One is to distribute the positive and negative signals of the power supply bus, respectively, in two different plugs; the other is to distribute the positive and negative signals of the same plug in different areas.

4. Full-link closed-loop verification method

The reliability of the system is determined by design, guaranteed by production and verified by tests. The development of electrical systems for launch vehicles is a complex systems engineering task, consisting of a number of subsystems or components, which involve electrical, pneumatic, hydraulic, structural, mechanical and other elements [15]. There are a lot of interactions, and it is prone to problems with key links in design, production, and assembly processes. In particular, the polarity issue in the signal transmission links is critical: if any single link exhibits polarity reversal, it may cause signal errors resulting in mission failure. For example, the attitude control loop is most typical. The European Vega rocket suffered a flight failure of VV17, which was caused by the

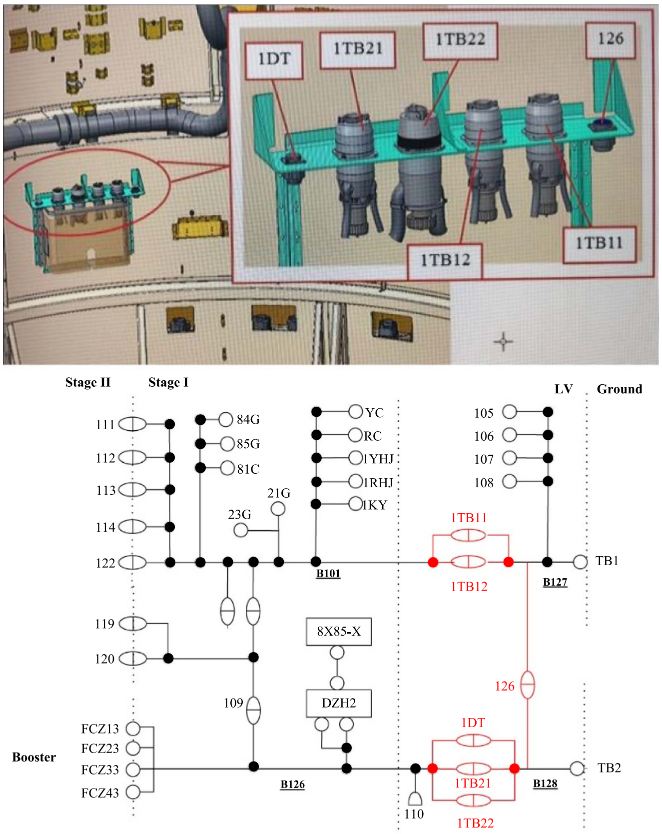


Figure 8. Improvement of the control cables: in the diagram, 1TB11, 1TB12, 1TB21, 1TB22 represent disconnect connectors added to the cable linking the rocket and the ground, which separate in a timed sequence after rocket launch.

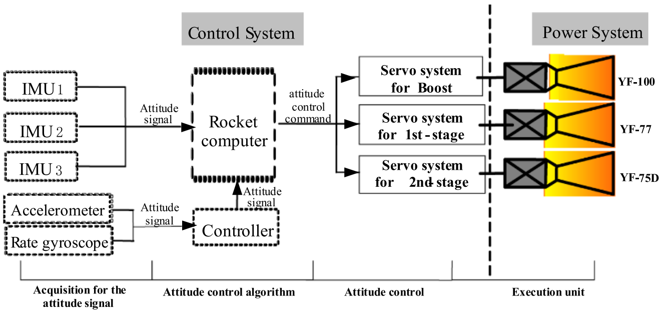


Figure 9. Schematic diagram of attitude control in powered-flight phase.

AVUM upper stage. The IEC concluded that the failure was due to the wrong routing and connection of the control lanes of the electro-mechanical actuators of the AVUM upper stage thrust vector control (TVC) system.

To address polarity issues commonly encountered during launch vehicle flight operations, engineers have implemented a comprehensive closed-loop verification methodology. This approach involves authentic simulation of signal input variations, signal processing, flight computation, and control

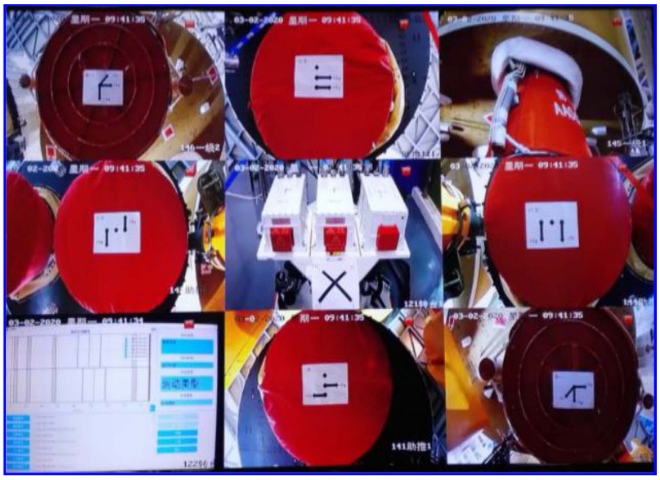


Figure 10. Polarity loop test for liquid rocket engine nozzle: the image displays the operational status of key equipment captured by cameras during testing. By combining these visuals, the coordination of actions can be assessed.

output generation throughout the flight envelope. Taking the attitude control chain as a representative case, the implementation flow comprises:

1) IMU situation simulation: Physically replicate vehicle attitude variations using inertial measurement unit (IMU) excitation;
2) On-board computer processing: Employ flight-qualified avionics for real-time attitude determination;
3) Servo command generation: Derive actuator control signals from computed attitude solutions;
4) TVC execution: Translate servo outputs into engine nozzle deflection;
5) Nozzle response validation: Engineers validate polarity correctness through visual inspection of nozzle deflection compliance with commanded trajectories.

This verification framework is rigorously applied throughout the vehicle production life cycle:

1) Pre-shipment testing: Conduct TVC polarity checks prior to launch vehicle transportation to the cosmodrome.
2) Launch site verification: Implement the polarity test of the whole loop by small turntable' program during launch campaign preparations.

4.1. Attitude control in powered-flight phase

As illustrated in the figure 9, the fundamental principle of rocket attitude control operates as follows: during flight, the rocket's orientation is continuously monitored by an IMU accelerometer, and gyroscopes. These sensors transmit real-time attitude data to the rocket computer [16]. The computer processes this information using predefined control algorithms, then commands servo mechanisms to actuate engine nozzle gimballing, thereby adjusting thrust vector alignment to ensure trajectory adherence. Crucially, the IMU-measured attitude must maintain strict synchronization with the nozzle deflection angles; any mismatch could lead to mission-critical control failures. Therefore, automated polarity validation protocols have become important in the development of rockets. According to the actual situation of the launch site, the CZ-5 development team implemented a 'Full- Loop Polarity Verification via Miniature Turntable' methodology. Special turntables are installed at the vehicle assembly building. During the electrical system test, three fiber-optic IMUs were mounted on the turntable and the servo mechanism was installed on the engine.

After the system is powered up, a special flight program is run, and the small turntable is rotated to simulate the three-axis attitude dynamics of the rocket body during the flight. According to the given control signal, the rocket computer commands the servo mechanism to execute TVC gimbal motions, and then drives the thrust vectoring actuation. At the same time, synchronously a specialized monitoring system is utilized to capture the multimedia records of the key information, as shown in the figure 10.

During the test, the full-link polarity from 'the IMU → FCC → TVC Servo → TCA signal chain' was validated through hardware-in-the-loop simulations replicating the ascent phase dynamics.

The detection method of polarity is an end-to-end closed-loop validation covering all subsystems.

4.2. Attitude control in the coasting phase

Chinese CZ-3B suffered a partial failure when launching the Indonesian satellite PALAPA-N1 in 2020 [17]. During the ballistic coast phase, the rocket body experienced progressively increasing roll rates and then induced divergent roll instability after the second ignition of the YF-75 cryogenic engine. The root cause of the accident is the wrong assembly of the cable plug of the inertial navigation system cable harness. As shown in figure 11, the adjacent nozzles 9 and 11 are of this feature.

In order to avoid the malfunction of attitude control thrusters, a reaction control system (RCS) nozzle of the RCS nozzles was adopted after the flight. An array of triaxial magnetometers were precision- mounted near the attitude nozzles, this process calculates the actual actuation timing of the TVC nozzles. During rocket flight simulations, engineers verify whether the nozzle actuation timing aligns with the predetermined sequence, thereby validating the polarity correctness of the control signal chain. Figure 12 is the recorded check result of the proper timing sequence.

The two methods mentioned above belong to quality management and include three main features:

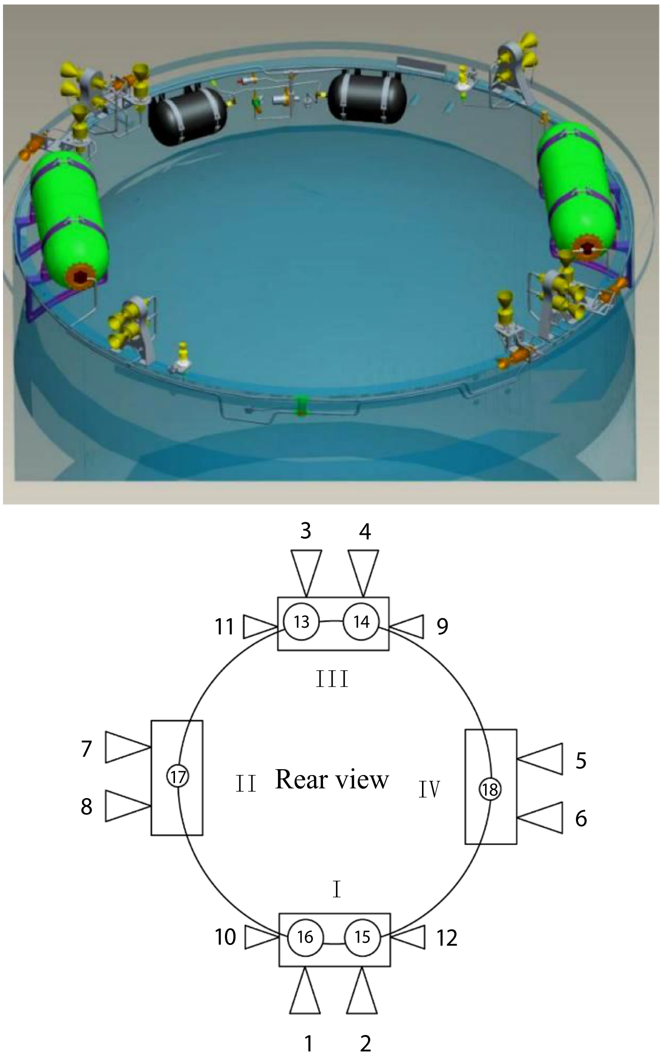


Figure 11. Schematic diagram of attitude control in the coasting phase.

(1) E2E: In one test, it includes the acquisition of attitude telemetry signals, the computation of attitude control algorithms, the generation of attitude control commands, and the actuator response validation.
(2) Physically-grounded verification principle: It should be confirmed by the power-on test of the equipment when conditions are available.
(3) Digital twin-based traceability framework: By means of image or video recording, the fault link can be quickly and accurately traced in the event of polarity problems.

Through a detection methodology of all elements and all links, the correctness of the electrical interface and the reliability of the system can be verified.

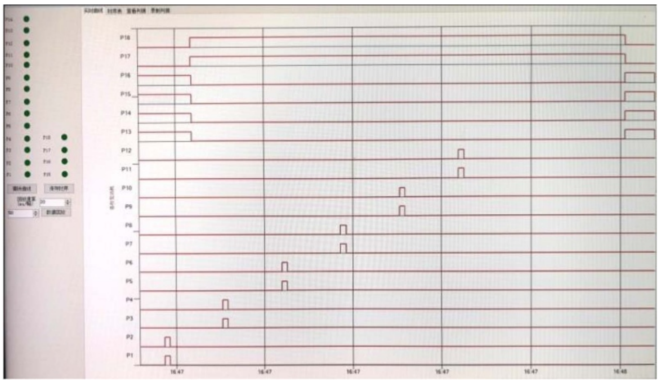


Figure 12. Recorded timing sequence of all nozzles: in the diagram, P1 to P18 represent the solenoid valves of the attitude control engines, which activate sequentially according to the predetermined timing.

5. Conclusion

The CZ-5 rocket, representing China's state-of-the-art large-scale launch vehicle technology, forms the backbone of future space missions and plays a pivotal role in the ambition of national initiatives such as the 'Chinese Lunar Exploration Program' and the 'China Manned Space Station'. The electrical system, acting as the rocket's central nervous system, consistently integrates reliability principles into every aspect of its development lifecycle.

This paper reviews the reliability considerations in the electrical system's design, development, and verification phases, highlighting examples like robust reconfiguration designs, fault-tolerant interfaces, and comprehensive, closed-loop verification methods for all components. The holistic commitment to reliability in the electrical system is a cornerstone for the successful execution of the CZ-5 rocket program, embodying the essence of reliability-centered engineering methodology throughout the rocket's development process. This rigorous approach not only underscores the present achievements but also sets the course for future advancements in the reliability design of rocket electrical systems.

With the advancement of electronic technology, launch vehicles are evolving toward 'smart rocket' development. The reliability of electrical systems will be further enhanced, mainly focusing on the following development directions [18, 19]:

1) Application of high-speed real-time bus systems.
   To address the growing demand for large-scale data communication and intelligent control/fault tolerance requirements in launch vehicles, time-triggered switched data networks are being adopted. For instance, the Ariane 6 and CZ-10 employ TTEthernet (time-triggered Ethernet) as its backbone network communication bus for the entire rocket electrical system [20].
2) Fault diagnosis technology based on FMEA/FTA results.
   During launch vehicle testing and pre-launch preparations, automated online evaluation of critical onboard parameters is conducted. Fault diagnosis and resolution are implemented using failure mode and effects analysis (FMEA) and fault tree analysis (FTA) results, enabling rapid issue resolution to improve launch reliability.
3) Intelligent fault adaptation technology.
   Through smart control technologies such as artificial intelligence and digital twins, real-time fault identification during rocket flight is achieved. This enables autonomous system reconfiguration using predefined strategies, including online trajectory replanning, guidance algorithm reconstruction, and attitude control system reconfiguration, thereby enhancing flight reliability [21].

Data availability statement

The data cannot be made publicly available upon publication because they are not available in a format that is sufficiently accessible or reusable by other researchers. The data that supports the findings of this study are available upon reasonable request from the authors.

Acknowledgments

The presented work is part of the project'Development of the new generation launch vehicle of China' financially sponsored by CNSA.

Conflict of interest

The authors declare no conflict of interest.

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