# Chapter 1
# Review, Prospect and Technical Challenge of Launch Vehicle

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## 1.1 Review on Development of Launch Vehicle

Following six decades of development, the technology of launch vehicle has progressed with respect to the dual action of demand traction and technical promotion, providing increasingly valuable high-tech services for society. Currently, the development of launch vehicle is progressing with respect to stronger capabilities, higher reliability, lowering costs, flexibility, and user convenience [1–3]. Retrospectively, the global development history of the launch vehicle technology can be roughly categorized into the following four stages with distinct characteristics of the decades (Fig. 1.1).

(1) Initial Development Stage (1950–1970s): This stage primarily solved the problems of zero-to-one, and furnished the basic demands of access to space.

(2) Space Shuttle Stage (1970–1990s): In this stage, the reliability and carrying capacity of launch vehicle have tremendously improved to meet the diverse launch demands, and concomitantly, the early phase of reusable technology developed.

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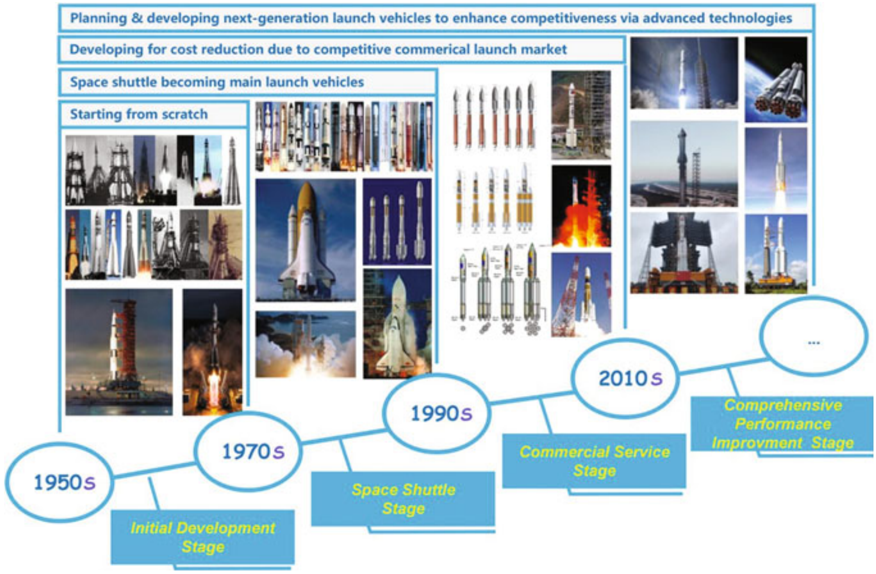


Fig. 1.1 Development stage of launch vehicle

(3) Commercial Service Stage (1990–2010s): International commercial launches flourished during this stage. To capture the international commercial launch market, the design and development of the launch vehicle weighed in the cost factors and more diversified mission adaptability demands.

(4) Comprehensive Performance Improvement Stage (2010–now): Owing to the stiff competition and incessant technical innovation, the launch vehicles during this stage have an improved comprehensive performance through the appropriation of the principles of modularization, serialization, and combination. By employing the advanced technologies such as the reusability and artificial intelligence, the comprehensive performance of the launch vehicle is fully enhanced. Therefore, the constantly emerging novel launch vehicles augment their competitiveness in the launch market [2, 3].

### *1.1.1 Initial Development Stage (1950–1970s)*

The emergence of the launch vehicle, on a global scale, began in the mid-1950s, and its development has been primarily based on the ballistic missile technology. During this stage, the United States and the Soviet Union occupied the leading position in the space competition. They solved the zero-to-one problem and developed several launch vehicle series with complex configurations.

The early American launch vehicles primarily include Juno, Thor, Delta, Atlas, Titan, and Vanguard. The first five models have been developed on the basis of the Jupiter medium-range missile, the Thor medium-range ballistic missile, the Atlas intercontinental ballistic missile, and the Titan intercontinental ballistic missile. Further, they were equipped with different upper stages such as Agena and Centaur, thus forming various different launch vehicle series. Concomitantly, based on the demands of the Apollo moon landing, the United States has developed the Saturn series on the basis of the newly developed high-thrust engines and large-diameter rocket bodies, including three types of Saturn I, Saturn IB, and Saturn V. During 1969–1972, a total of seven manned moon missions were carried out.

The Saturn V launch vehicle adopts a three-stage configuration. The first stage employs five high-thrust F-1 liquid oxygen and kerosene engines, and the second and third stages use five and one J-2 liquid hydrogen and liquid oxygen engines, respectively. The full length is 110.6 m, the maximum diameter 10.06 m, the take-off mass 2946 t, the carrying capacity in low-earth orbit 120 t, and the carrying capacity in the earth-moon transfer orbit 50 t. Among them, F-1 is the liquid launch vehicle engine with the highest single-nozzle thrust in history, and its ground thrust has been 6806 kN.

Since 1957, on the basis of strategic ballistic missiles, the Soviet Union has successfully developed Sputnik, Luna, Vostok, Voskhod, Soyuz, Molniya, Kosmos, Tsyklon, and other launch vehicles. It has also launched a large number of satellites, and manned or unmanned spaceships, space stations, moon probes, and Mars and Venus probes, and other spacecrafts, thus creating multiple world records in human spaceflight. The first six models belong to the R-7 launch vehicle family, which is a series of launch vehicles derived from the first intercontinental ballistic missile, viz., the Soviet R-7. The Sputnik is the first launch vehicle for the first artificial earth satellite launched by the Soviet Union. Its basic stage is the most launched one, for any launch vehicle in the world, hitherto. It consists of a core stage bundled with four liquid boosters using liquid oxygen and kerosene propellant, and is equipped with different second and upper stages, thus, forming a huge family of launch vehicle. To compete with the United States in the human lunar mission, the Soviet Union developed the N-1 heavy-lift launch vehicle, though all of the four launches failed. Furthermore, the Soviet Union also developed the Proton series, which employ the conventional propellants to launch large spacecrafts such as the Proton Satellite and the space station cabins.

Meanwhile, in Europe, France, and the United Kingdom began to develop their own launch vehicles in 1960. France developed the Diamant series on the basis of the sounding rockets and missiles. The United Kingdom developed the Black Arrow and Blue Streak launch vehicles. Concurrently, several European countries established the European Launcher Development Organization and developed the Europa series of launch vehicles.

Japan developed the L-series and M-series of launch vehicles based on the sounding rocket technology, and launched its first artificial earth satellite with the L-4S launch vehicle, in February 1970.

Meanwhile, China developed the Long March (LM) 1 and 2 launch vehicles. In April 1970, the LM-1 launch vehicle successfully launched the first artificial satellite of China, i.e., Dongfanghong-1, thus, laying a solid foundation for the space industry of China.

### *1.1.2 Space Shuttle Stage (1970–1990s)*

Since 1970s, the reusable launch vehicle technology has been favored. Both the United States and the Soviet Union have focused on the development of reusable aerospace transportation system. The hazardous implementation of the program has also affected the development of expendable launch vehicles. They primarily improved the carrying capacity and reliability, besides promoting the advances in technology.

By 1972, the United States concentrated on the development of partially reusable space shuttles, expecting a significant reduction in space launch costs through the reuse of vehicles, to eventually replace the expendable launch vehicles. The space shuttle consists of an external storage tank, a solid booster and an orbiter, among which the solid booster and orbiter can be recycled and reused. The space shuttle first flew in 1981. In 1982, the U.S. government announced that it would replace the expendable launch vehicles such as the Atlas, Delta, and Titan, with the space shuttle to launch all U.S. payloads. The painful lessons from the Space Shuttle Challenger accident in 1986, persuaded the U.S. government to resume the use of expendable launch vehicles, thus establishing a vehicle team consisting of space shuttles and expendable launch vehicles. Prior 1982 and post 1986, the United States upgraded and improved the Atlas, Delta, and Titan launch vehicles by improving the engine performance, bundling solid boosters, lengthening the storage tank, and replacing the upper stage. Further, they formed the series of Atlas G, Atlas H, Atlas I and Atlas II, Delta 1000, Delta2000, Delta3000 and Delta II, Titan III/IV and Titan IV series, and other launch vehicles to enhance the carrying capacity comparable to the space shuttle. Among them, the Delta II launch vehicle became the primary medium-lift launch vehicle of the United States during 1990s.

The United States produced a total of six space shuttles. However, owing to the consideration of the aging and safety of the space shuttles, besides the high cost, complex operation, and long operating cycle, they finally have decided to announce the decommission of the Space Shuttle after the final flight in 2011.

By December 1971, the Soviet Union began research and development on the reusable space transportation systems. Further, by exploiting their own advantages in the liquid launch vehicle engines, they began developing the Energia heavy-lift launch vehicle by 1976. The launch vehicle has a full length of 58.7m, a diameter of 7.75m, a takeoff mass of about 2220t, a takeoff thrust of about 3616t, and a carrying capacity in low-earth orbit of about 100t. The primary task is to transport the reusable orbiter, i.e., Buran Space Shuttle, and launch large payloads into the low-earth space. The Buran Space Shuttle made only one unmanned flight. Concurrently, the Soviet

Union carried out a standardized upgrade of the Soyuz launch vehicle to form the Soyuz U and U2 launch vehicles, with improved carrying performance. Further, they developed the Zenit 2 launch vehicle using the technology of the Energia launch vehicle engine. It is mainly used in the domestic military satellites and has rapid response capabilities. However, subsequent to 1990s, the Zenit series have gradually been utilized for international commercial space launches.

Since 1973, Europe began to develop Ariane launch vehicles based on the Europa and Diamant launch vehicles. By the early 1990s, the Ariane launch vehicles have steadily developed from Ariane 1 to Ariane 2, Ariane 3, and Ariane 4 by improving the performance, lengthening the propellant storage tank, bundling solid or liquid boosters, and increasing the number of bundled boosters. The carrying capacity has been quadrupled, and the payload adaptability was also greatly improved.

To master the liquid launch vehicle technology for launching large satellites, and obtain medium, high, and geosynchronous orbit satellite launch capabilities, Japan adapted the Thor-Delta launch vehicle technology from the United States in the 1970s, and hence developed the N series launch vehicles. Further in the 1980s, they developed the H-I launch vehicles with a higher payload capacity.

Meanwhile, China primarily developed the LM-2C and LM-3 launch vehicles. Among them, the LM-2C has been improved on the basis of the LM-2, which in turn, enhanced the carrying capacity and reliability to a certain extent. LM-3 is a three-stage launch vehicle developed on the basis of the LM-2C launch vehicle. Its three stages use liquid hydrogen and oxygen cryogenic propellant, and are primarily used to launch geosynchronous orbit satellites.

India began to develop the four-stage solid launch vehicle, Satellite Launch Vehicle 3 (SLV-3), on the basis of the sounding rockets in 1973, and successfully sent the Rohini Satellite into low-earth orbit in 1980, and then developed Augmented Satellite Launch Vehicle (ASLV) on the basis of SLV-3.

### *1.1.3 Commercial Service Stage (1990–2010s)*

By 1990s, the launch vehicle technology entered a new stage of development. Competition in the international commercial launch market has intensified, and the launch demands for high-mass communication satellite have increased. Most nations have begun the development and improvement programs for low-cost launch vehicles.

The U.S. Air Force began to implement the development program of Evolved Expendable Launch Vehicle (EELV) in 1994. The goal has been to reduce launch costs, improve the reliability, and the capture of international commercial launch market while meeting the domestic launch demands. The program finally gave birth to the series of Atlas V and Delta IV launch vehicles, and both of which have fully inherited the advantages of the previous models. Further, they adopted modular design ideas, and advanced power and control technology, to reduce the launch costs and improve the carrying capacity, reliability and operability, besides replacing the original launch vehicle model at the beginning of the 21st century. The primary common modules of the Atlas V series include the common core stage, common centaur upper stage, solid binding booster, and payload fairing. The common core stage uses one RD-180 engine, which can be categorized into 400 and 500 series according to different combinations. They can meet the launch demands of various medium-lift payloads, besides taking into account the launch requirements of the U.S. military's payloads. The Delta IV series employs a large-diameter common core (5.08 m) bundled with different types of boosters, and achieves multiple carrying capacities through modular combination, including Delta 4 medium-lift, modified Delta IV medium-lift and Delta IV Heavy. The common core stage employs the newly developed low-cost RS-68 engine, and both the common core stage and the second stage use liquid hydrogen (oxygen) propellant.

Following the disintegration of the Soviet Union in 1991, Russia made improvements over the Proton and Soyuz launch vehicles, forming multiple launch vehicles such as Proton M, Soyuz ST, and Soyuz 2. Further, they equipped them with Breeze M and Fregat upper stages, and debuted them into the commercial launch market. Russia has also altered its decommissioned and reduced strategic ballistic missiles into launch vehicles such as Start, Rockot, Dnepr, Volna, Strela, and Shtil, and introduced them into the commercial launch market. Furthermore, Russia began to develop environmentally friendly, non-toxic, and advanced-performance Angara series, based on the idea of Generalization, Serialization, and Combination, by 1994. By this step they hoped to replace the major existing launch vehicles of Russia with Angara series. Nevertheless, only the Angara 1.2 and 5 configurations have performed a total of three launch missions, hitherto.

Europe has developed the Ariane 5 in accordance with the demands of the commercial launch market, besides the development and utilization of low-earth orbit. It is the world's first high-thrust launch vehicle designed with a large-diameter and less-stage scheme, and has been continuously improved with respect to the performance of the launch vehicle. Ariane 5 series including Ariane 5G, 5ES, 5ECA, 5ECB, and other models have been formed, which can perform single-satellite-in-one-launch and multiple-satellites-in-one-launch missions, and gradually become the driving force in the international commercial launch market. Concurrently, Europe started the development of the Vega small launch vehicle as a supplement to the Ariane 5 and Soyuz, for launching small governmental and commercial payloads. Vega first flew in 2012. Meanwhile, to fill the gap in the medium-lift carrying capacity, the Russian Soyuz ST has been introduced.

The Ariane 5 series are all in the two-stage configuration. The core stage is equipped with one Vulcan liquid oxygen and hydrogen engine, bundled with two solid boosters, and the carrying capacity for geosynchronous transfer orbit (GTO) can reach 6.9–10.5 t.

Japan has developed the H-IIA series and H-IIB based on the H-II launch vehicle through modular design. This is to meet the diversified launch demands and enhance its competitiveness in the space launch market, and improve the reliability of launch vehicle. The H-IIA series are all in the two-stage configuration bundled with different numbers of boosters, including HII-A202, H-IIA2022, H-IIA2024, and H-IIA204. The maximum carrying capacity for GTO is 5.7 t. The first stage is powered by one

LE-7A liquid oxygen & liquid hydrogen engine, and the second stage is powered by one LE-5B liquid oxygen and hydrogen engine. The H-IIB launch vehicle has an increased diameter in the first stage, viz., from 4 m to 5.3 m on the basis of H-IIA, and installs two LE-7A engines in the first stage, besides the carrying capacity for GTO reaching 8 t.

China has introduced the developed LM-2E, LM-2C/SM, and LM-3A series of launch vehicle into the international commercial launch market, and successfully developed the LM-2F launch vehicle. LM-2F is a two-stage launch vehicle bundled with four boosters, based on LM-2E and developed in accordance with the mission requirements of human spaceflight. The reliability index reaches 0.97 and the safety index reaches 0.997. The first flight was on November 20, 1999, and it successfully launched the Shenzhou-1 test spacecraft. The first successful human launch was on October 15, 2003.

During this stage, India has successively developed a Polar Satellite Launch Vehicle (PSLV) and a Geosynchronous Satellite Launch Vehicle (GSLV), which are capable of launching medium, large, and geosynchronous orbit satellites.

### *1.1.4 Comprehensive Performance Improvement Stage (2010s–Now)*

Since 2010, the United States, Russia, Europe, and Japan, based on the long-term development goals, are actualizing the upgrades through the layout in developing the next generation of launch vehicles. They are based on the development principles of modularization, serialization, and combination, besides benefiting from the improvement of economy. Further, they have utilized the advanced technology such as the reusability and artificial intelligence, to enhance the comprehensive market competitiveness of the launch vehicle [2, 3].

Aided by the efficient management and technical innovation, SpaceX has pursued research and application on vertical take-off and landing technology, and gradually occupied more than half of the international space commercial launch market with marked price advantages for Falcon 9 and Falcon heavy. Its primary focus is on the development of the Superheavy-Starship transportation system. Superheavy-Starship aims to actualize the future airline-flight-mode space transportation. It is a common vehicle that can perform services such as global rapid transportation, space shuttle transportation, earth-moon transfer transportation, lunar landing and ascent, forecasting Mars exploration transportation. It has been selected by NASA as the lunar lander in the Artemis program. Affected by multiple-factors such as the risk of outsourcing Russian engine supply and the return of American manufacturing, ULA initiated developing a Vulcan launch vehicle with certain intelligence. It has achieved different carrying capacities by bundling multiple solid boosters and upgrading upper stage performance, and is intended to significantly reduce the launch costs, compete with SpaceX, and eventually replaced the EELV launch vehicle. Furthermore, Blue

Origin is also developing the New Glenn launch vehicle during the same period. Concurrently, United States is fast developing the Space Launch System (SLS) heavy-lift launch vehicle to support its Artemis program and manned deep space exploration strategy [4].

To enhance the competitiveness, Russia has proposed Soyuz 5 and 6 launch vehicles. Both of them adopt a simple two-stage serial configuration and employ the first stage of liquid oxygen and kerosene, and a second stage with liquid oxygen and kerosene, or liquid hydrogen and liquid oxygen. They will replace the Soyuz 2 series of launch vehicles of similar capabilities in the future. Furthermore, the first stage of the two launch vehicles can also be utilized as the core stage or the booster module of the Russian heavy-lift launch vehicle. As a medium-lift launch vehicle, the Soyuz 5 and 6 have the characteristics of a simple configuration and strong modularization (generalization). Technically, they have the potential to be the primary force of the next-generation medium-lift launch vehicles of Russia. Russia has also proposed the Amur reusable launch vehicle scheme that employs the liquid oxygen and methane propellant, and the first stage can be recycled and reused vertically.

Europe and Japan have proposed new launch vehicle updating programs, viz., Ariane 6 and H-III, respectively, in response to the stiffening competition in the international commercial launch market. Both of the programs factor in cost reduction as the first priority, conduct development in response to the market demand, and avoid pursuing exclusive technical advancement. The Ariane 6 inherits most of the design basis and mature technology of the Ariane 5, and will replace the Ariane 5 and Soyuz ST in future [5]. Meanwhile, with the rapid development of small satellite market, some commerical aerospace companies develope various small reusable rocket, such as Spanish launch startup PLD Space's Miura 1 reusable suborbital rocket and British startup Orbex' Prime launch vehicle, holding low-cost and rapid-launch features.

H-III launch vehicle of Japan fully inherits the mature technology of the H-IIA/IIB, while focusing on improving the design in reducing costs and improving reliability. The first stage uses two to three LE-9 liquid oxygen and hydrogen engines. Both the second stage and the solid booster have been improved with respect to the H-2A/2B. Different numbers of boosters are bundled to achieve different carrying capacities. The carrying capacity for GTO can reach 7t. Concurrently, Japan has developed the Epsilon solid launch vehicle based on the concept of intelligent measurement, launch, and control to significantly reduce the number of ground testers and the launch costs [6].

Aiming the international advanced level and the demands of launch vehicle upgrading, China has successfully developed a new generation of launch vehicles based on 120 t liquid oxygen and kerosene engines and 50 t liquid oxygen and hydrogen engines, covering the launch mission demands of low, medium, and high orbit spacecrafts. The new-generation launch vehicles of China is a series of vehicles according to the design concept of Generalization, Serialization, and Combination, founded on "one series, two engines, and three modules", and aiming at the reality and urgent demands of the space development of China. This includes LM-5/5B built based on 5m diameter modules, LM-6, LM-7/7A, and LM-8 built based on 3.35 m diameter modules. The maximum carrying capacity in low-earth orbit reaches 25 t.

The maximum carrying capacity for GTO is 14 t. These launch vehicles first flew successively in 2015-2021. Among them, the LM-5 launched the Tianwen-1 probe and the Chang'e-5 probe into space, and achieved the first Mars landing &patrol and lunar sampling & return of China. Further, the LM-5B launched the China Space Station modules to the low-earth orbit. Furthermore, China is currently making technical improvements to launch vehicles based on the demands of low-cost and high-reliability, and preparing for future upgrading, besides concurrently developing the reusable technology and super heavy-lift launch vehicles.

## 1.2 Development Prospect of Launch Vehicle

With the development of human society, the space field has become an important territory for human survival and development, particularly in the 21st century. The demand for various space missions is fast increasing, the space activities become more and more frequent, and the big space era is coming.

(1) Mankind's dependence on space is increasing on a daily basis, and space technology is playing an important role.

Since the 1960s, hundreds of space science and exploration missions have been carried out around the world. Human footprints have spread across the eight planets of the solar system, and scientific cognition has engendered new breakthroughs. With respect to satellite applications and services, the communication satellite system has steadily evolved, and the accuracy of the navigation satellites has grown manifold. Further, the public service capabilities of remote sensing satellites have been enhanced, thus providing humans with highly accurate monitoring and warning of weather, environment, and disasters. The economic scale of the space industry is burgeoning with impending expansions.

Predictably, the space field will be an important territory for human survival and development in future, whereas the cislunar space serves an outpost for human exploration of space. The space industry, owing to its expansion, will also take the lead in entering a new era of cislunar economy.

(2) The current world space missions have developed to a new stage of large-scale access to space.

Recently, the demands for global ubiquitous network access and Internet of Things connection services have been on the rise, and the development of low-orbit communication have accentuated it. Nearly tens of thousands of giant communication constellation projects represented by Starlink, OneWeb constellation, and Hongyan constellation have emerged in sequence, and the development of low-orbit Internet, satellite Internet of things, and other fields will accelerate. Concurrently, with the development of space technology, and the demand for a large-scale space infrastructure represented by space power stations and space factories, besides human lunar exploration and construction of lunar bases, have become increasingly strong. Space missions have eventually developed to a new stage represented by large-scale Inter-

**Table 1.1** Forecast of scale demand for access to space in 2045

| Space activities | 2045/t |
|---|---|
| Communication/navigation/remote sensing | 3000 |
| Space science exploration and experiment | 4000 |
| On-orbit service and maintenance | 4000 |
| Space tourism and global rapid transportation | 40000 |
| Space key infrastructure | 5000 |
| Deep space exploration | 2000 |
| Space energy | 40000 |
| Resource exploration and utilization | 10000 |
| Space-based warning | 2000 |
| Space safety | 4000 |
| Space medicine/agriculture/manufacture | 5000 |
| Space environmental monitoring and warning | 1000 |
| Others | 5000 |
| **Subtotal** | 125000 |

net constellations, large-scale space resource development and utilization, large-scale lunar exploration, and large-scale deep space exploration. According to the course of the global space industry, and based on the current foundation, it is estimated that by 2045, the global annual scale demand for access to space will exceed 100,000 tons, as listed in the Table 1.1.

(3) Commercial spaceflight is advancing rapidly, and the space industry is showing a new direction of development.

Owing to the relentless development of space technology and the increasing scale of the space industry, commercial spaceflight such as commercial launch vehicles, low-orbit Internet constellations, and commercial remote sensing have been rapidly promoted. The space industry is displaying a new course of development, and will eventually expand to the fields of space tourism, global airline-flight-mode rapid transportation, space resource development, energy utilization, on-orbit manufacturing, medicine, and health in the future.

With the continuous development of space technology, the scale of future space missions will become colossal, and the scope of space applications and services will become extensive, besides a rampant commercialization of the space industry. The space industry will be more integrated with human society, economy, and livelihood of people. To encounter the demands of the large-scale access to space in the future, the Space Transportation Revolution needs to be implemented. A Revolution Era of Space Transportation is impending, which has the following basic characteristics [3].

- Manifold increase of carrying capacity;
- Substantial Cost reduction;
- Enhancement of Reliability and safety;
- Profound effect on society and life;
- Intelligent delivery vehicles;
- Airline-flight-mode operation and management;
- Fast launch, convenient, and flexible;
- Form a large-scale industry.

The new demand also brings many challenges. It is necessary to adopt the latest scientific and technological achievements to the maximum in the existing ways of access to space. Concurrently applying and cultivating the reusable technology and intelligent autonomous technology, to meet the future demand for large-scale and low-cost access to space.

## 1.3 Current Development Status of Launch Vehicle Reusable Technology

From the perspective of the history of launch vehicles, expendable launch vehicles are still the mainstream method for nations to enter space. However, the era of the large-scale and low-cost access to space, particularly with the successive proposal of the airline-flight-mode space transportation system and the mission concept of global arrival within an hour, leads to the rapid development of reusable technology.

Reusable launch vehicles can greatly reduce the cost of access to space through multiple uses and cost sharing, which is the course of development for vehicles in the future.

According to the current development situation, reusable space transportation systems can be divided into two categories, viz., axisymmetric configuration and lifting body configuration.

### *1.3.1 Reusable Space Transportation System in Axisymmetric Configuration*

The reusable transportation system based on the traditional axisymmetric configuration primarily recycles and reuses its stages. Therefore, the stage recycling is a major issue. According to the recycling method of the stage, it can be categorized into the parachute reusable launch vehicles and the vertical take-off and vertical landing (VTVL) reusable launch vehicles. Furthermore, fairing recycling has also begun to be practiced and applied.

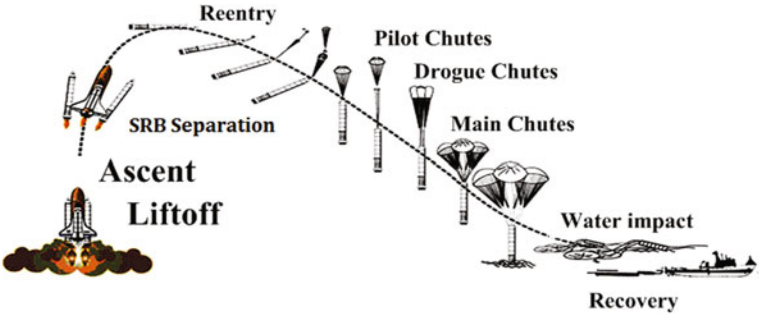


**Fig. 1.2** Space shuttle SRB recovery process

#### 1.3.1.1 Parachute Recovery Reusable Launch Vehicle

For parachute recovery reusable launch vehicles, following the completion of the mission of the launch vehicle, the parachute is deployed to decelerate the vehicle during the return, to a speed of tens of meters per second, and finally, to fall on land or at sea for recycle and reuse. The examples are Kistler's K-1 launch vehicle, NASA's space shuttle booster, and ULA's Vulcan launch vehicle.

(1) Parachute recovery of the space shuttle booster at sea
The recovery of the solid rocket booster (SRB) of the space shuttle uses a large group parachute. The SRB unit integrates the ascent, reentry, and recovery subsystems. The integrated booster subsystem includes the thrust vector control, auxiliary power unit, avionics, pyrotechnic signal, range safety system, parachute, thermal protection, and water recovery system. The technical difficulties of SRB include the subsystem integration, thermal environment and harsh load environment (including falling water impact). Multiple subsystems have been improved to meet the reusable requirements. Each booster deploys three main parachutes to slow down and finally land on the sea. The SRB recovery process is shown in Fig. 1.2 [7].

(2) Parachute recovery of K-1
Kistler's K-1 launch vehicle program started in 1993, expecting to reduce the launch cost of the launch vehicle through reusability, for commercial launches. K-1 is a two-stage fully reusable vehicle, and the first stage adopts a recovery scheme based on parachute and cushion airbag. Following the release of the payload, the second stage reentry and return to the launch site also employ the recovery scheme based on parachute and cushion airbag.

Owing to the development of the two-stage fully reusable vehicle being hazardous, and the unsure project funding, the development plan of K-1 is fluctuating. Despite certain tests and verifications, it has not been introduced for practical applications. However, the vast majority of development tests on recovery and landing system have been completed, and the feasibility of the recovery approach based on group parachute and airbag has been verified through the demonstration and verification test on the aircraft. The K-1 recovery process is shown in Fig. 1.3 [8, 9].

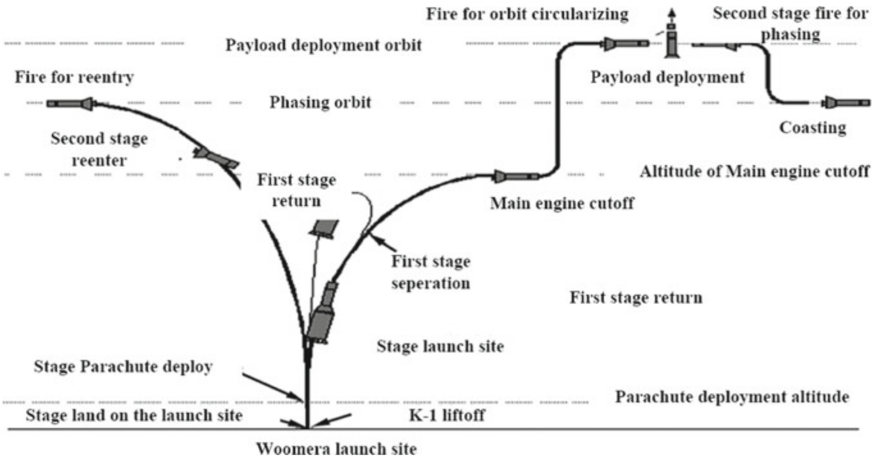


**Fig. 1.3** The K-1 recovery process

(3) Vulcan aerial recovery
In April 2015, ULA announced the Vulcan program of the heavy-lift launch vehicle. The Vulcan will use the Sensible Modular Autonomous Return Technology (SMART) technology to achieve the recovery and reuse of the stage.

Subsequent to the separation of the first and second stages, the first stage engine of the launch vehicle will be separated from the first stage and re-enter the atmosphere under the protection of an inflatable heat shield. It will be decelerated by the parachute, and finally recovered in the air by a helicopter. ULA stated that the cost of the propulsion system accounts for 65% of the total cost of the first stage, and the recycling of the first stage engine will reduce the cost of the first stage propulsion system by 90%. ULA claimed that the SMART recovery project is only the beginning of the launch vehicle recovery program of the company. In future, ULA will also recover other launch vehicle components to further reduce the launch costs.

(4) Fairing recovery of Falcon 9
The fairing generally adopts an extremely light and thin carbon fiber sandwich structure, which mandates precise manufacturing and testing before application. The production cost accounts for about 10% of the total cost of a single launch. Generally, after the launch vehicle reaches the Karman Line at a height of 100 km, the rocket becomes unaffected by the atmosphere, and the fairing automatically separates and falls. If the fairing can be recovered for re-launch, it will further reduce the cost of manufacturing and launch.

SpaceX leads the research and practice of the fairing recovery and in May 2017, for the first time, actualized the controlled fairing splashing down in the ocean, which employed ships for salvage and recovery. Since the internal structure does not account for the corrosion resistance requirements, the fairing recovered after splashing down in the ocean must be processed before reuse, which increases the cost and difficulty

**Fig. 1.4** The launch vehicle whose first stage is for parachute recovery

of recycling. To handle this issue, SpaceX uses modified vessels for the direct capture and recovery to prevent the fairing from contact with seawater. On June 25, 2019, after the deployment of the equipment of cushion nets on ships, the net capture of fairing in the air was realized for the first time. This denotes that SpaceX has successfully verified the two methods of fairing recovery. However, owing to the relatively low probability of the net capture of the fairing in the air in actual flight missions, the scheme for net capture in the air has been cancelled.

(5) The aerial recovery of the first stage of the Rocket Lab's Electron launch vehicle
On August 7, 2019, Rocket Lab, co-sponsored by New Zealand and the United States, proposed a program for the first stage recovery in the air for its Electron small launch vehicle.

Electron is a two-stage launch vehicle with a length of 17 m, a diameter of 1.2 m, a take-off mass of 10.5 t, and a carrying capacity in 500 km sun-synchronous orbit (SSO) of 150 kg. The first stage of the launch vehicle employs nine Rutherford engines, and the second stage employs one vacuum Rutherford engine. The Electron utilizes advanced carbon fiber composite materials to design a high-strength and light-weight flight structure. The first stage structure is light in weight and suitable for the helicopter hooking recovery in the air. Following the separation of the first stage, the main engine stops decelerating, or deploys inflatable airbags to decelerate. Finally, a two-stage parachute is deployed to decelerate. The main parachute is a parafoil, and the helicopter is employed for the aerial hooking recovery in the air.

(6) Parachute recovery technology in China
In terms of the parachute recovery of launch vehicles, China has completed the study on the parachute recovery scheme and the airdrop test and verification for the liquid oxygen and methane first stage.

The launch vehicle whose first stage is for parachute recovery is a small two-stage liquid launch vehicle with a total length of about 29 m. The overall layout is shown in Fig. 1.4. The take-off mass is about 100 tons. When launched from the Jiuquan launch site, the carrying capacity for 700 km SSO exceeds 650 kg.

To reduce the launch cost of the launch vehicle, the first stage is recovered and reused. The recovery landing system adopts the scheme of two stabilizing parachutes and two decelerating parachutes, besides three main parachutes. This decelerates the separated first stage, and employs the airbag system arranged at the front and rear ends of the first stage to cushion the landing process, thus, reducing the impact load in the landing process and the damage to the vehicle body caused by the impact load. The cushion airbag is a combination of inner and outer airbags. The outer airbag cushions the landing process of the first stage. The inner airbag is encapsulated in

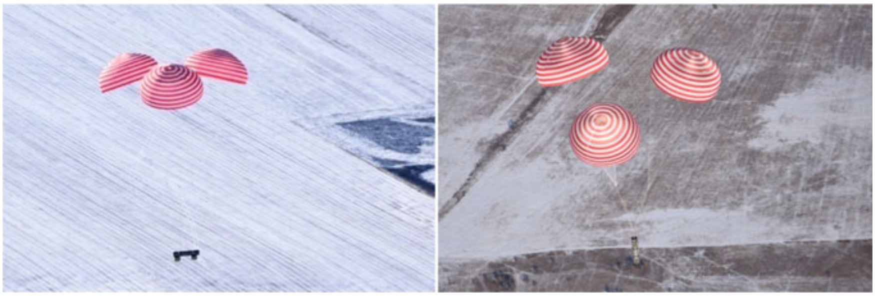


**Fig. 1.5** The airdrop test for the parachute recovery of first stage

the outer airbag, and functions as a support to the first stage of the launch vehicle following the landing, so that the first stage does not directly impact the ground.

China has also completed the airdrop test for a group parachute recovery of the launch vehicle stage, and has developed the scale model for airdrop test of the first stage of launch vehicle and the scale test prototype of the group parachute system. The airdrop test uses a helicopter as the airdrop platform, and carries and releases the scale prototype of the group parachute and cushion airbag system, and the scale model of the first stage. In the test, the decelerating parachute and the main parachute have been deployed in sequence, and hence, reached a steady falling speed. Finally, the scale model of the first stage has been brought to the ground. The airbag deployment and landing cushion have been normal, and the stage model was successfully recovered (Fig. 1.5).

#### 1.3.1.2 VTVL Reusable Launch Vehicle

For VTVL reusable launch vehicle, following the completion of launch mission, it restarts the main engine to decelerate the stage during the return process, and finally employs the landing legs to accurately land on the predetermined position, for e.g., SpaceX's Falcon 9 and Blue Origin's New Glenn.

The earliest use of the vertical return recovery was the Delta clipper scheme proposed by McDonnell Douglas in the 1990s. It was designed to utilize the VTVL technology to achieve single-stage-to-orbit and reuse. Delta clipper has conducted a total of twelve flight tests, with a maximum flight altitude of 3155 m, and verified the technologies of the VTVL, fast flyback, and simplified ground support [10].

The first stage of the Falcon 9 adopts the VTVL scheme, and the first stage will return to the launch site from the sub-orbit after the stage separation, or land vertically down range. To develop the reusable Falcon 9, SpaceX has developed a diversified and progressively-developing verification plan of the reusable technology. The recovery operations for the first stage of Falcon 9 have carried out a large number of experimental verifications, and has successfully carried out dozens of offshore platform and land recovery. A single first stage module has performed up to eleven launch missions (by December 2021). Concurrently, on the basis of the Falcon 9, two core stages have been added to form the Falcon Heavy. All three core stages can be landed vertically and reused.

SpaceX's Superheavy-Starship system applies the VTVL reusable technology for the design of the heavy-lift launch vehicles, and it is expected to become the world's first two-stage fully reusable heavy-lift launch vehicle. Since the launch vehicle has been proposed in 2016, its scheme has been iteratively optimized. Following the transition of the Big Falcon Rocket (BFR), the combined scheme of Superheavy and Starship was finally determined in 2018.

While continuously optimizing the scheme, SpaceX has adopted a model of prototype verification iteration and dual-line research and development (R&D), to achieve a rapid verification and optimization of the related technologies. Since 2019, it has experienced tests such as the Starhopper series, MK series, and SN series, and achieved a 10-km high-altitude flight test in the SN15 test. Currently, it is advancing its work towards the direct flying into the orbit.

Furthermore, Blue Origin has also proposed the New Glenn series of launch vehicle which adopts the vertical return recovery of the first stage.

The New Glenn has two-stage and three-stage configurations. The diameter of the launch vehicle is about 7m. The first stage is equipped with seven BE-4 liquid oxygen and methane engines with a thrust of 17000 kN. Further, the first stage is separated in the ascending section and returns vertically to land on the offshore platform for recovery. Unlike the Falcon 9, which uses a grid fin, the recovery process employs an aerodynamic control surface to implement the aerodynamic control. Moreover, Blue Origin's suborbital human launch vehicle of the New Shepard, has successfully completed multiple recovery and reuse.

DLR, CNES, and JAXA are jointly developing the CALLISTO aircraft based on their experience in the vertical landing technology. All the three organizations will use the aircraft to verify their own guidance and control algorithms. The maximum flight altitude and the speed can reach 40 km and Mach 2, respectively. On this basis, the European Space Agency (ESA) will develop the Themis launch vehicle. As the milestone verification project of the European reusable technology, it is categorized into two processes, viz., single engine and three engines. Its maximum speed can reach Mach 6–8, and it can simulate the whole process of the dynamic deceleration and aerodynamic deceleration when the launch vehicle enters the dense atmosphere at high speed. The proven key reusable technology will be applied to the Ariane Next series of launch vehicles.

In 2020, the Roscosmos officially released its new generation of commercial reusable launch vehicle Amur. The Amur launch vehicle has a height of 55 m, a takeoff mass 360 t, and a diameter 4.1 m. It uses liquid oxygen and methane propellant with a two-stage configuration. The first stage of the launch vehicle takes off and lands vertically, and is equipped with five RD-0169A engines with a sea level thrust of 100 t. The second stage of the launch vehicle is expendable, and uses a vacuum version of the RD-0169V engine, same as the first stage, with a vacuum thrust of about 110 t. The first stage of the launch vehicle is initially designed for 10 times reuse, and the long-term design goal is 100 times.

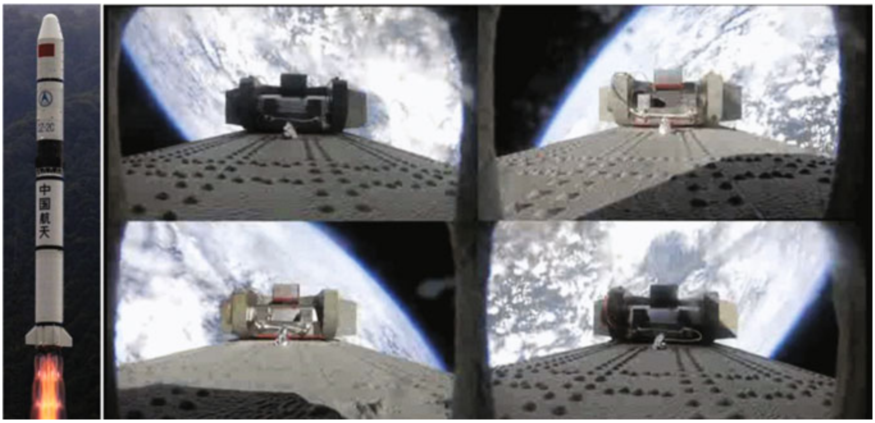


**Fig. 1.6** Flight test for the gridfin based landing zone control (LM-2C)

China is also actively carrying out research and application of VTVL key technologies. Currently, it has broken through the manufacturing and control technology of titanium alloy integral casting grid fin, and carried out a flight test and verification of the landing zone control for the first stage of a LM-2C in 2019 (Fig. 1.6).

The LM-8 has carried out research on key reusable technologies with the goal of vertical recovery [11]. To verify the key technology, powered by the UAV turbojet engine, a small aircraft Peacock has been designed, and the verification of the guidance and control algorithm has been carried out. The composition of the Peacock aircraft is displayed in Fig. 1.7.

The slenderness and thrust-to-weight ratios of the Peacock aircraft simulate the parameters of the LM-8. All electronic equipment adopts commercial off the shelf (COTS), and the flying altitude is controlled near 400 m. This verifies the adaptability of the convex optimization algorithm in the embedded computing environment.

Based on the second stage of the LM-7, a VTVL flight test has been designed. It is powered by liquid oxygen and kerosene engine, and the flight altitude is controlled at 2 km. The aircraft operates four engines during the ascent phase. Two of the engines are turned off at the highest point, and the remaining two continue delivering the power for reverse thrust. Furthermore, to verify the guidance and control algorithms, the following technologies of the aircraft will be tested, such as the landing cushion mechanisms, relative navigation, and rapid post-processing of liquid oxygen and kerosene engines after landing. Among them, the landing cushion mechanism adopts a triangular overall scheme, which has multiple functions of folding and retracting, landing cushion, deployment deceleration, and locking and bearing. Its composition is displayed in Fig. 1.8.

Since the existing Long March launch vehicles in service do not employ multiple engines in parallel, the guidance and control algorithm [12] under the condition of limited throttling capability, which causes high thrust-to-weight ratio of the landing stage (thrust-to-weight ratio greater than 2.0) has been studied. Under the premise

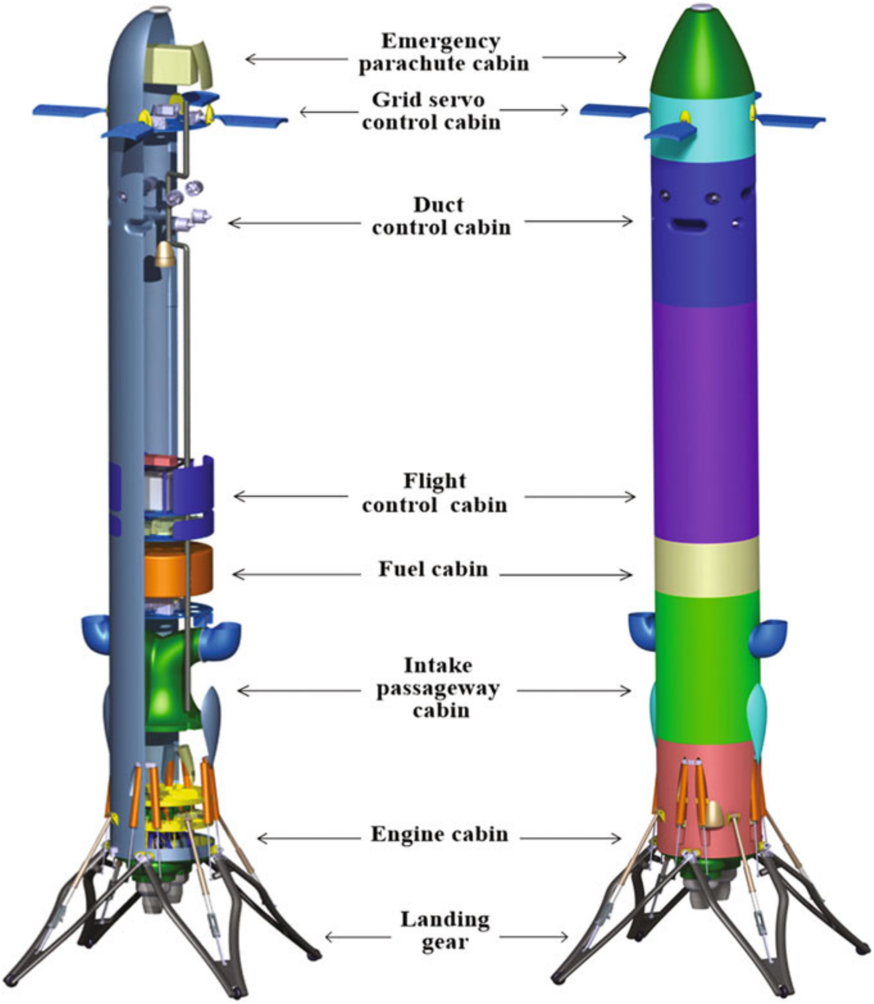
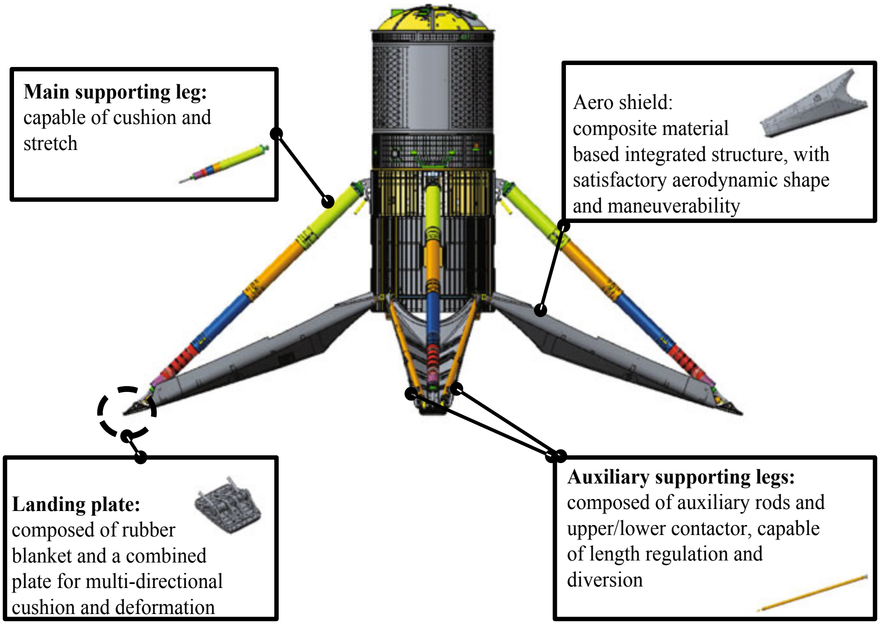


**Fig. 1.7** The Peacock Testbed for the verifications of GNC algorithm

of unchanging engine configuration, the foundation has been laid for the upgrading of the in-service launch vehicles to reusable launch vehicle.



**Main supporting leg:** capable of cushion and stretch

Aero shield: composite material based integrated structure, with satisfactory aerodynamic shape and maneuverability

**Landing plate:** composed of rubber blanket and a combined plate for multi-directional cushion and deformation

**Auxiliary supporting legs:** composed of auxiliary rods and upper/lower contactor, capable of length regulation and diversion

**Fig. 1.8** Supporting legs of the Peacock aircraft

## *1.3.2 Reusable Space Transportation System in Lifting-body Configuration*

### 1.3.2.1 Rocket Powered Lifting-Body Reusable Launch Vehicle

(1) Reusable first stage

Reusable first stage refers to a vehicle with autonomously controllable returns, lands horizontally, and is reused after transporting the payload from the surface of the earth to the suborbital space. It is the first stage of a two-stage orbiting space transportation system. Typical launch vehicles include the Reusable Booster System (RBS) and XS-1 from the United States, the Baikal from Russia and the RLV-TD from India.

The RBS is a reusable vehicle development program launched by the U.S. Air Force to realize the operational responsive space (ORS) capability. The program is directed by the U.S. Air Force Research Laboratory (AFRL). The U.S. Air Force has demonstrated that the RBS concept is a reliable method to meet its future demand of rapid access to space [11].

The RBS system uses a vertical launch mode. The first stage and the upper stage fly to the separation point and then return to the launch site, thus landing on the runway like an airplane.

The U.S. Air Force is contemplating the use of rocket-powered boosting to implement the return of the first stage. Following the separation of the rocket-powered booster from the upper stage, it performs a return maneuver first, and then returns to the launch site through an unpowered reentry gliding flight before landing.

The turnover cycle of the RBS is 8 hours, of which 2 hours are used for launch preparation, and 6 hours are used for inspection and maintenance of the airport runway after landing. The RBS engine can be reused 10 times, and the booster can be reused 100 times. If there are eight flights each year, then its launch cost will be reduced by about 50% [13].

In 2013, the U.S. Defense Advanced Research Projects Agency (DARPA) relayed the U.S. Air Force to continue the research and testing of reusable booster system. Thus, they launched a new Experimental Space Aircraft (XS-1) Program, headed by the leading industrial sector in pre-research, for a continuous improvement of key technologies. Further, they laid a technical foundation for the future development of practical vehicles [14]. However, owing to economic factors, technical difficulties, and low carrying efficiency, it was finally canceled in early 2020.

The Baikal Program of Russia began by the end of 1998. The Baikal is a winged flyback booster that can fly back to the launch site and land like an airplane, automatically. It can be reused 100 times. Certain structural and propulsion components of the Baikal's common core stage booster have adopted mature technologies, including deployable wings, an all-moving tail, and an auxiliary turbojet engine.

(2) Reusable orbiter stage

Reusable orbiter stage refers to the reusable launch vehicle that is transported by the first stage vehicle to the sub-orbit, and then separates and powers its own main engine to transport the payload to the required orbit. Further, it can stay in orbit for a long period and perform various orbital service mission, on-demand return, and horizontal landing. Typical vehicles include the Space Shuttle Orbiter of the United States and the Buran Space Shuttle Orbiter of the Soviet Union.

- Space shuttle orbiter

The Space Shuttle Orbiter of the United States first flew in 1981, and was later decommissioned in 2011. According to the design requirements, each orbiter can be reused 100 times, and each time, a maximum of 29.5 t payload can be transported to the low-earth orbit, besides returning a payload of 14.5 t to the ground. The orbiter can carry 3 to 7 people and stay in the orbit for 7 to 30 days to perform tasks such as rendezvous, docking, parking, crew/cargo transportation, space testing, satellite launch, overhaul, and recovery. Hitherto, the six space shuttle orbiters of NASA have carried out a total of 135 missions.

- Buran space shuttle orbiter

By 1978, the Soviet Union began to develop the Buran space shuttle orbiter, which was successfully launched in November 1988.

The Buran space shuttle orbiter is 36 m long and 16 m high, with a triangular wingspan of 24 m, a fuselage diameter of 5.6 m, and a take-off mass of 105 t (14.3 times that of the mass of Soyuz manned spaceship), and a landing weight of 82 t. It was launched by using the newly developed Energia heavy-lift launch vehicle at that time.

**Fig. 1.9** Launching satellites by aerospace craft

The Soviet Union produced a total of two Buran test aircrafts. On November 15, 1988, the Energia sent the unmanned Buran space shuttle orbiter into a predetermined orbit of 250 km. The Buran automatically orbited the earth twice. Subsequent to 3 hours in orbit, it returned to the ground on the same day, as scheduled, and landed at an airport 12 km away from the launch site. The first flight of the Buran was successful. The flight test of another test aircraft was canceled owing to economic influence.

On July 16, 2021, the vehicle of China for sub-orbit reusable flight test and verification took off at the Jiuquan Satellite Launch Center. Following the completion of the flight according to the set procedure, it horizontally landed at the Alxa Right Banner Airport in a smooth manner. The first flight was a complete success. The suborbital reusable vehicle can be employed as a stage of the lifting-body rocket-powered reusable space transportation system.

#### 1.3.2.2 Combined-Cycle Powered Reusable Launch Vehicle

The combined-cycle powered reusable launch vehicle draws the main power from the combined-cycle powered engine, and adopts the method of horizontal take-off and horizontal landing (HTHL). According to the operating range of the engine, the vehicle can be employed as the first or the second stage.

The combined-cycle powered reusable launch vehicle has the potential to achieve single-stage-to-orbit. It can transport payloads from the ground to the required low-earth orbit, return on demand, and land horizontally. It is a method of implementation for a completely reusable space transportation system.

The SABRE aerospace project is a two-stage-to-orbit combined-cycle powered reusable launch vehicle project that uses the SABRE engine to launch satellites.

Currently, the project has received investment from Boeing, Rolls-Royce, and BAE Systems, and completed the assembly of the first pre-cooler prototype (HTX)and related auxiliary equipment, at the newly built TF2 test station in Colorado, USA (Fig. 1.9).

Skylon is a new generation of single-stage-to-orbit aerospace vehicle being developed by REL in collaboration with other European research institutions [16].

The overall design of the first Skylon (Skylon C1) has been completed. The total take-off mass is about 275 t. It has a slender fuselage design, with the fuselage length nearly 85 m and a wingspan 25 m, with a built-in propellant storage and load capsules. Two SABRE engines have been installed symmetrically at the tip, which has the ability to transport a payload of 12 m in length, 4.6 m in diameter, and 12 t in weight into a 300 km orbit.

## 1.4 Development Status of Launch Vehicle Intelligent Autonomous Technology

With the development of space technology, high-density launch of vehicles has become normal, and reusability has become a development trend, besides ever changing mission requirements. Higher demands are proposed for the performance such as reliability, convenience, maintainability, mission upgradability, on-orbit deployment, and mission planning, which necessitates the development of intelligent autonomous technology for the space transportation systems.

(1) Demand for high-density launch and quick response
In future, launch vehicle will encounter continuous high-density launch missions, so as to promote the construction of space infrastructure, and to meet the booming demand of commercial spaceflight. Internet constellation programs continue to advance. It mandates the shortening of the launch preparation time and improving the launch reliability, which raises stringent requirements for the launch vehicle testing, and launch capabilities.

(2) Demand for reusable and airline-flight-mode transportation
Owing to the development of aerospace technology and the demand for large-scale development of earth-moon space, the reusable space transportation system will eventually shift towards airline-flight-mode. This requires strong autonomous inspection, maintenance, and flight control capabilities, and the intelligent autonomous technology can provide strong support.

(3) Demand for improvement of the adaptation capability to multiple missions and flight faults

Owing to the increasing demand for access to space, besides space utilization missions in the future, the space transportation systems shall have intelligent and autonomous flight control and on-orbit deployment capabilities. Further, they should meet the requirements of the flight failure response capabilities, and the high-precision and diversified transfer of spacecraft. Currently, the failures owing to various reasons are generally coped with or adapted to, by means of redundancy and backup. The means are relatively simple and the system cost is relatively high, besides the types of failures to be dealt with being relatively limited. With the expansion of the system scale, the mission complexity of the launch vehicle continues to increase, and higher requirements are placed on the flight failure handling capabilities of the launch vehicle.

Owing to the above-mentioned demands, it has acquired the ability to autonomously perceive its own state and the external environment, besides the continuous improvement in autonomous response and learning. This is achieved through the application of intelligent autonomous technology to the transportation system, during the launch and flight. It can independently complete the launch preparations and deal with uncertainties. During the flight, based on the results of intelligent perception of itself and the external environment, it has the ability to adapt and respond to the environmental changes and failures, independently, to achieve efficient and reliable access to space.

Currently, certain space faring nations in the world have taken the lead in conducting research and related practices for the autonomous flight control of the propulsion systems and actuator failures, besides intelligent autonomous technology applications such as the autonomous operation control technology.

### *1.4.1 Propulsion System Fault Identification and Mission Reconstruction*

In the domestic and foreign space history, failures of the launch vehicle are more frequent owing to the failure of propulsion system. According to statistics, by 1970s, the United States had launched thousands of medium and long-range missiles, and launch vehicles, of which about 50% of the flight failures were due to propulsion system failures. Between 1990 and 2015, 64 foreign launch vehicles failed due to propulsion system failures, accounting for 51% of all launch failures.

Through intelligent autonomous technology, it can enhance the ability of the launch vehicle to actively adapt to propulsion failures and autonomous decision-making, and either to continue or degrade for completing tasks.

The space faring nations, viz., United States and Russia, have incorporated typical failure modes into the design and verification process, and made their main launch vehicles have a certain degree of failure adaptability by planning the mission capacity margins or adopting propulsion redundancy in the configuration selection.

(1) United States
United States was the first country to carry out research on the fault identification and diagnosis technology. It carried out research and application of the launch vehicle fault adaptability in the 1960s. The well-known engine manufacturer Rocketdyne has made statistics on the failures of seven types of engines (MA-3, MA-5, RS-27, F1, H1, J-2, SSME) during the development process. A total of 85,000 failures have been counted out of the 2500 engines that have conducted 1,000 flights, and the failure records were evaluated, screened, classified, and summarized into sixteen failure modes for the engine failure analysis and prediction. The Saturn series have

adopted “path adaptive guidance” that includes flight path optimization. During the launch of Apollo 6 in 1968, two engines of Saturn V were shut down, owing to the failure in the second stage. However, the control system stabilized the launch vehicle and prolonged the engine working time to propel the launch vehicle into the orbit, normally. In 1985, the safety system on the Challenger space shuttle shut down the malfunctioning No. 1 engine in due time, which did not have a fatal impact on the launch. Falcon 9 ground take-off allows one engine failure, and allows two engine failures after flying for a period of time. In October 2012 and March 2020, the Falcon 9 had two engine failures during the flight, and both of instances have been overcome, and the payload was successfully transported to the orbit through reconfiguration.

(2) Russia
Russia also has advanced technical experience in the launch vehicle diagnosis and health management technologies. Typical systems include the health monitoring and life assessment system that is developed for the high-power liquid launch vehicle engine (RD-170), and the orbiter real-time automatic monitoring and prediction system developed for the Buran Space Shuttle. Furthermore, the N1 launch vehicle has the capability to complete subsequent tasks with the remaining engines even after the failure of two engines during the flight.

### *1.4.2 Fault Identification and Control Reconfiguration of Actuator*

The China’s LM-3B has applied the fault diagnosis and reconstruction algorithm of the attitude control thrusters. For the failure of attitude control thrusters, the information of the control system inertial measurement device is utilized. Furthermore, based on the priori motion information generated by the thruster control, the corresponding relationship of the command and expected angle of acceleration are employed to make a logical analysis and judgment, and hence, to complete the nozzle failure identification. The control reconfiguration is executed according to the identification result, and the control strategy is adjusted in real time. The effectiveness of the technology had been verified during the launch mission of the LM-3B in July 2020, and the onboard test verification was successfully completed. Further, the application flight was successfully realized in the subsequent missions. On December 22, 2020, China’s new-generation LM-8had successfully achieved its first flight. This flight has added the ability of online flight failure recognition during coast phase, and can autonomously perform attitude control reconfiguration under specific failure conditions (Fig. 1.10).

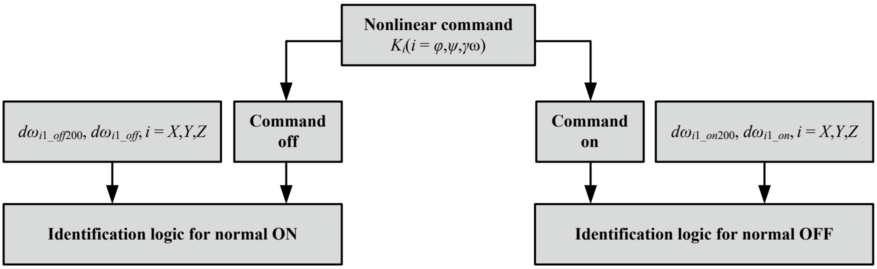


**Fig. 1.10** The principles for fault diagnosis for attitude thrusters

### 1.4.3 Autonomous Control Technology

For the pre-launch ground test and load operation of the launch vehicles, the autonomous operation control technology can actualize the failure prediction and diagnosis, anomaly detection, fault detection, and isolation of the system and components before the launch. Different from the conventional ground process of launch vehicles, the technology can be applied to launch vehicle engine testing, ground loading, and future in-situ resource utilization of the moon or Mars surface. This can reduce the operation and maintenance costs, improve the effectiveness of the system, expand the surface operation and maintenance tasks for lunar and Mars missions, and minimize the tasks with manned operations (such as operations at dangerous location and teleoperations).

The autonomous operation of the launch vehicle can be achieved by integrating the technologies with respect to the health management, command and control, computing systems, decision-making, control software, intelligent components, and devices. Among them, the integrated system health management technology integrates the data, information, and knowledge distributed in each unit of the system for anomaly detection, fault diagnosis, and trend prediction. Further, it provides the users with the integrated perception of the status of important units in the system for the decision-making of the user [17].

The first stage of Falcon 9R has the ability to repeatedly execute multiple missions. Its health detection and diagnosis system monitor the health of the reusable launch vehicle body and engine during the full life cycle. In-depth research has been conducted on the detection content, intelligent detection methods, detection procedures and maintenance methods. Further, the reuse intelligent evaluation technologies, relevant in the post recovery of the launch vehicle body, have been developed, so that the reusable launch vehicle stage can complete the detection and maintenance, and restore the ability to launch in a relatively short time.

To apply autonomous operation technology to ground propellant loading, NASA implemented the research program on Integrated Ground Operations Demonstration Units (IGODU), which is intended for the advancement of processing and command control technologies related to the cryogenic operations, and reduction of the complexity of the operating and launch facilities, thereby reducing launch costs [18]. Further, NASA has built a Simulated Propellant Loading System (SPLS). Taking into account the discrepancies between the program, and the final autonomous loading and operation, NASA launched the Autonomous Propellant Loading (APL) program [19] to verify the autonomous parallel loading, health monitoring, failure detection, and autonomous emergency handling technologies of multiple storage tanks and multiple media. Compared with the demonstration and verification of SPLS, the APL program expects to increase the maturity of the autonomous loading from level IV to V. Further, it employs the real cryogenic propellant and software in ground support equipment (GSE) or its integration to improve the model and expand capabilities to support more complex operations.

Based on the improvement in the maturity of the autonomous loading technology, the Atlas V has been left unattended from the start of –7.5 h core stage propellant loading to ignition and launch. The Delta IV has also been unattended from the –5.5 h propellant loading before the launch. The Falcon 9 has realized the unattended front end of the launch from the commencement of the loading.

In terms of the launch control applications, generally the launch cycle of the expendable launch vehicle is more than two weeks, and the launch service period is exceedingly long. Meanwhile, there are more personnel involved in the launch, and the demand for human resources is greater. In contrast, the development team of the Japan's Epsilon has applied autonomous operation and control technology for the launch control process of the launch vehicle. This step has simplified the launch system and pre-launch process of the launch vehicles, shortened the launch vehicle's launch preparation time to only 6 days, and reduced the human resource requirements. The launch vehicle adopts novel communication architecture and is connected to the ground support facilities through a high-speed network, making the launch operation safer and simpler. It became the first launch vehicle of Japan that can be controlled from outside the restricted area of the launch site [20].

## 1.5 Future Development Technical Challenge of Reusable and Intelligent Autonomous Technologies

### *1.5.1 Technical Challenge of Reusable Technology*

The reusable technology has become an important technical development for launch vehicle. The arrival of the era of large-scale and low-cost access to space has also brought more technical challenges against the development of reuse technologies.

For the reusable transportation system in the axisymmetric configuration, the technical challenges of the parachute recovery and VTVL methods are as follows.

(1) The parachute recovery method has a low carrying capacity loss and relatively high technological maturity. However, this method mandates the design of a large group parachute system. The deployment area of the parachute system can reach

hundreds to thousands of square meters. The flexibility of the parachute system has a great impact to the recovery process. Restricted by the initial conditions of recovery, it may also be necessary to open the parachute at supersonic speeds. If the land-based parachute recovery is adopted, the large-scale cushioning airbags need to be designed. If helicopters are employed for the parachute recovery in air, it is necessary to ensure the stability of the capture. Therefore, the main technical challenges include the following technology of large-scale group parachute, large-scale cushioning airbag, supersonic parachute opening, fairing parachute recovery, and aerial capture of the recycled body.

(2) With the development of the technology of the throttling engine and advanced control theory, the VTVL methods have been investigated in the past decade. The Falcon 9 of the SpaceX has achieved dozens of VTVL missions. Europe, Russia, China, and other countries have put forward verification plan for the reuse of the VTVL technology. For the VTVL methods, the flight profile of the vehicle during the return process is complicated. Further, the system interference caused by the unknown shear wind and structural deviation, unmodeled dynamics, such as elasticity/aerodynamic coupling in the vehicle body, and liquid sloshing due to large-scale attitude adjustment, bring great challenges to the high-precision landing of the recovery stage. Furthermore, the landing support mechanism is also the key to ensuring the vertical and stable recovery, and there are also technical challenges in the mechanism design and reliable deployment. Therefore, the primary technical challenges of the VTVL method include the trajectory design and optimization technology, return high-precision guidance and control technology, and landing support technology.

The technical challenges of the rocket powered and the combined-cycle powered reusable transportation system in the lifting-body configuration are given as follows.

(1) Although the United States, Russia, Europe, and China have carried out different degrees of flight demonstration verification for the rocket-powered lifting-body reusable transportation system, even the United States has put the space shuttle into service as the main space transport vehicle from 1981 to 2011. However, in future, tremendous challenges are in waiting owing to the quest for affordable, technologically advanced, and feasible transportation system solutions. The solutions are inclusive of the overall design and optimization technology, aerodynamic layout, aerodynamic characteristics design technology, heat-resistant materials and structure technology, reuse maintenance and operation technology, high-precision integrated guidance, navigation, and control technology for on-orbit flight and reentry.

(2) For the combined-cycle powered reusable transportation system, the technical foundation is relatively weak and the design is complex. The primary focus is on the design and development of the combined-cycle powered engine. Moreover, under the combined-cycle powered mode, different factors such as the engine performance, structural load, and aerodynamic heat have multi-dimensional constraints on the design parameters such as the flight dynamic pressure, overload, and attack angle change. These parameters that will result in the overall scheme design faces the problem of multi-factor coupling and narrow feasible region. Furthermore, the combined-cycle powered flight area is large and the environment changes drastically. To exploit

the advantages of the combined-cycle powered propulsion performance, timely and stable switching of propulsion forms is particularly important, and the scheme design is complicated. Therefore, the primary challenges of the combined-cycle powered propulsion mode include the integrated design and of the flight body and propulsion in wide area, and the integrated control of the flight body and propulsion.

### *1.5.2 Technical Challenge of Intelligent Autonomous Technology*

The emergence of artificial intelligence technology has created novel opportunities for the development of space technology. Compared with the unmanned driving of other modes of transport, the flight of the launch vehicle is unmanned from the beginning, but it is an automatic flight in a relatively definite design scenario, and thus its autonomy and intelligence are insufficient. Owing to the increasing frequency of space launches, incidents of various abnormalities have also increased significantly. If intelligent autonomous technology can achieve results in response to emergencies, it will promote the development of commercial spaceflight and a new economic ecology.

Many NASA scientists and engineers prefer to talk about machine learning and autonomy rather than artificial intelligence [21]. Currently, there are a few reliable applications of AI in the real-time flight of vehicles. However, it is more prominent in data mining, image recognition, failure diagnosis, and other fields, and the required real-time computing capability far exceeds that of embedded computing platforms in aircrafts. This phenomenon has also improved. According to reports, the enhanced Proton M has used the AI technology. The in-flight fail-safe performance level has been improved by introducing artificial intelligence elements. The launch vehicle control system automatically identifies and offsets potential failures related to propelling units, such as the steering actuators and engines. The mission objective is thus being achieved [22]. It can be seen that the AI technology is primarily expected to handle non-nominal working conditions.

AI technology can be utilized during the entire life cycle of launch vehicle including research, development, operation, and support. Further, the AI technology has several other areas of application, which can comprehensively build an intelligent transportation ecosystem including research and verification, production and manufacturing, testing and launch, flight, and evaluation. For example, explore the digital development process of the launch vehicles to improve the design efficiency; carry out more realistic virtual demonstration and verification tests of combination of virtuality and reality to break the bottleneck of the difference between the space and the earth, and the difficulty of physical testing; realize the autonomy of ground operations, reduce manpower requirements and improve rapid response capabilities to meet the challenges of normalization of multiple launches; realize the information sharing of the rocket-ground equipment through high-speed networks, and utilize data mining, intelligent diagnosis, and other technologies to lay foundation for failure detection, isolation, system reconfiguration and improvement of the reliability of flight; develop intelligent manufacturing technology to improve the production efficiency and product qualification rate and support the development of space economy.

However, realizing more intelligent flights through AI technology has always been the biggest challenge for the intelligent autonomous technology of launch vehicles. From the perspective of control, the different characteristics of the launch vehicles, civil aviation aircrafts, and automobiles, in terms of route planning, guidance and control [23]. On the computing platforms with limited computing capability and power consumption and with less data support, and under very strict real-time requirements, it takes more arduous efforts to realize the intelligent or autonomous flight.

## 1.6 Conclusions

The mankind pace of space exploration has never stopped, and recently the demand has increased substantially. The era of space economy is coming. As the only tool of access to space, the launch vehicle has ushered in new development opportunities and challenges under the dual action of the demand traction and technology promotion. Currently, space missions show diversified development demands of large-scale, low-cost, high-reliability, and airline-flight-mode, which impose additional stringent requirements on the balance among performance, cost and reliability, mission adaptability, and rapid response capabilities of the launch vehicle.

Reusable and intelligent autonomous technologies have branded a distinctive time imprint for the development of the current vehicles. Falcon9 of SpaceX has been reused by VTVL, and has been put into commercial operation. Various new launch vehicles featuring vertical take-off, horizontal, or parachute landing are also under steady development. The reusable launch vehicles will provide technical and economic feasibility for large-scale access to space, making future space activities more diversified and frequent. This requires the vehicle to not only meet one-time or specific target tasks, but also adapt to changing demands and new environments that have never been explored. This is precisely the field where the application of intelligent autonomous technology is expected.

Realization of the intelligent or autonomous flight of the vehicle mandates the collaborative optimization of multiple disciplines. Particularly, the control system will play an important role as the nerve center of the vehicle. Owing to the development of information technology, the performance of the control system has been significantly improved. Therefore, the expectations from the control system are retrained to complete various predetermined tasks according to the content planned in advance, besides the ability to autonomously deal with various emergencies encountered in flight, maximum reduction of the dependence on the ground measurement and control personnel, reduced pre-launch preparations, and improved mission response and survivability. Transition from the automatic control to autonomous control will be an important step towards smart launch vehicles.

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