Perspective

The View of Micropropulsion Technology for China’s Advanced Small Platforms in Deep Space

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In this paper, micropropulsion systems are analyzed in conjunction with the various mission requirements of China’s deep space exploration. As a great challenge facing the world, deep space exploration can be enabled only in a few countries with a success rate of around 50%. With the advancement of spacecraft and scientific instruments, it is now feasible to build small and low-cost spacecraft for a variety of deep space missions. As spacecraft become smaller, there is a need for proper micropropulsion systems. Examples of propulsion system selections for deep space exploration are discussed with a focus on products developed by Beijing Institute of Control Engineering (BICE). The requirements for propulsion systems are different in lunar/interplanetary exploration and gravitational wave detection. Chemical propulsion is selected for fast orbit transfer and electric propulsion for increasing scientific payloads. Cold gas propulsion and microelectric propulsion are good choices for space-based gravitational wave detection due to the capability of variable thrust output at the micro-Newton level. The paper also introduces the sub-1-U micropropulsion modules developed by BICE with satisfactory performance in flight tests, which are promising propulsion systems for small deep space platforms. A small probe with an electric sail propulsion system has been proposed for the future solar system boundary exploration of China. The electric sail serves as not only a propellant-free thruster but also a detector probing the properties of the space medium.

1. Introduction

Since the first deep space exploration 60 years ago, hundreds of missions have been carried out, with a success rate of around 50% [1]. Limited by budget and technology, only a few countries, including the United States, Russia, United Kingdom, France, and Japan, are capable of manufacturing spacecraft for deep space exploration at this stage [2]. China began its deep space exploration with the launch of the Chang’e-1 satellite in 2007 and has seen rapid development in recent years with the success of the Chang’e-5, Tianwen-1, and Tianqin-1 projects [3–6]. Most spacecraft have a total mass above the ton level; however, as technology in aerospace and scientific instruments has advanced, the capabilities of small platforms have been greatly improved. It is now possible to construct micro- and nanosatellites for deep-space exploration.

Propulsion systems are essential in most space missions, especially for deep space exploration missions [7, 8]. Compared to Earth orbiting satellites, spacecraft for deep space exploration have higher requirements for the propulsion system, particularly in terms of fuel consumption. Spacecraft with a mass of about fifty to hundreds of kilogram typically have one or more of the following types: monopropellant system, bipropellant system, ion system, and Hall system.

For the CubeSat-like platform with total mass less than 20 kg, integration of a propulsion system was quite difficult in the past, due to the constraints of size, mass, and power. The requirements for such propulsion systems are lightweight, low-power consumption, small size, and enough flexibility to integrate with the other subsystems. Attitude and orbital maneuvering capabilities of satellites for position control, drag compensation, and deorbiting maneuvers are becoming increasingly important. To meet the strict
requirements, micropropulsion modules with various technologies were proposed. For example, some modules are packed with electric thrusters without complex propellant management system, such as a passive fed electrospray thruster and a microcathode arc thruster (µCAT) [9, 10], whereas others with traditional thrusters are self-pressurized, without high-pressure gas tanks. The deep space missions and the propulsion systems of the platform discussed in this article are primarily based on products developed by Beijing Institute of Control Engineering (BICE), which has specialization in the control and propulsion systems of spacecraft and has the accomplishment of China’s 90% of satellites and spacecraft.

2. Deep Space Missions and Propulsion Systems

To meet the needs of various occasions, several micropropulsion modules have been developed. The selection of propulsion system primarily depends on the mission. The cold gas propulsion has relatively low thrust, but it has high accuracy and high reliability, so the technology is suitable for the microsatellites with a mass of less than 10 kg or platforms that require high precision control. The chemical propulsion has the highest thrust level and flexible total impulse. The electric propulsion has a high total impulse and low thrust. For missions with extreme distances, electric propulsion has the advantage of saving fuel for more payloads.

2.1. Propulsion Systems for Lunar Exploration. The far side of the Moon is a unique place for scientific investigations. Queqiao, a relay communication satellite, is one of the most important and innovative components of the Chang’e-4 lunar exploration mission [11]. It was sent into a halo orbit near the Earth–Moon L2 point. Launched with Queqiao were two scientific microsatellites, named Longjiang-1 and Longjiang-2 also flying to the Moon. For quick transfer to the Moon’s orbit, both Queqiao and Longjiang have chemical propulsion; however, Queqiao satellite is 10 times heavier than Longjiang satellites, so that the propulsion systems are quite different.

Queqiao was built based on the CAST100 platform, with a total mass of 448.7 kg [12]. After an extensive tradeoff, the hydrazine monopropellant system was selected for its simplicity and reliability over the bipropellant system. It is the first monopropellant system used in the Chinese Lunar Exploration Program. For increased reliability, it is fully redundant with two branches, and with 70 L fuel tank for each branch (shown in Figure 1). The system has four 20 N thrusters for orbital control and twelve 5 N thrusters for attitude control. The propulsion system can provide the satellite with a velocity increment (ΔV) more than 550 m/s. On the May 21st, 2018, Queqiao was launched by CZ-4C rocket into a lunar elliptical orbit. Thanks to a 203 m/s impulse burn provided by four 20 N thrusters, the swingby propelled Queqiao toward the L2 point, some 65,000 km from the Moon.

To make the most of the capacity of CZ-4C the rocket, Longjiang-1 and Longjiang-2 were launched together with Queqiao, and they both have a mass of 47 kg, carrying light-weight equipment [13]. The satellites were to be flown in close 300 × 3000 km orbits, as shown in Figure 2, to allow for astronomical interferometry. Longjiang-2 entered a 350 × 13700 km lunar orbit on May 25th. The propulsion subsystem (shown in Figure 3) was specially developed by BICE to meet all the stringent weight and envelope requirements. Each twin has a 16 kg hydrazine-loaded monopropellant system with four 5 N thrusters and four 0.2 N thrusters. The dry weight of the propulsion system is 7.1 kg. The whole subsystem was highly integrated, and all of the other instruments were arranged around it. This configuration cuts the system’s dry weight by 30%.

Electric propulsion technologies, such as ion thrusters and Hall thrusters, are efficient in accelerating particles of the propellant by electric and magnetic field, resulting in a high \( I_{sp} \).

The first demonstration of electric propulsion system to achieve large-scale orbit transfer is European Space Agency’s (ESA) Small Missions for Advanced Research in Technology- (SMART-) 1 [14–16]. The 370 kg satellite was equipped with a 1.5 kW Hall thruster providing 90 mN thrust at the \( I_{sp} \) of 1600 s. SMART-1 was launched in September 2006, and it took about 2 months to enter the Moon’s orbit.

2.2. Micro-Newton Propulsion Systems for Tianqin-1

Another example of propulsion system selection is the gravitational wave detection missions. Only detectable from the space, the low-frequency gravitational wave (typically from 0.1 MHz to 1 Hz) has the broadest detection frequency range and the most diverse set of sources. Gravitational waves are always described as tiny ripples in the fabric of spacetime, squeeze, and stretch space periodically. Space-based gravitational wave probes measure the minute distance changes between devices that are only affected by gravity. Most space-based projects, such as LISA, Tianqin, Taiji, and DECIGO, require platforms to compensate for nongravitational
forces such as light pressure and solar wind in order to achieve a "drag-free" state. Requirements for propulsion system are that the thrust precision needs to reach 0.1 μN, and that thrust noise level should be controlled under 0.1 μN/Hz^{1/2}. Cold gas thrusters and μCAT were developed specifically for Tianqin-1 by BICE for a "drag-free" state.

As the path-finder for Tianqin mission, Tianqin-1 (TQ-1) was successfully launched on December 20th, 2019 from the Taiyuan Satellite Launch Center with the primary objectives of testing the inertial sensor, micro-Newton propulsion, drag-free control, and laser interferometry [3, 6]. The satellite completed its startup phase on December 21st, 2019 and had been functioning normally since then. The cold gas thrusters demonstrated a thrust resolution of 0.1 μN and a thrust noise of 0.3 μN/Hz^{1/2} at 0.1 Hz. The residual noise of the satellite with drag-free control is 3×10^{-9} m/s^2/Hz^{1/2} at 0.1 Hz. In addition, the μCAT also demonstrated the thrust variable capabilities for future missions.

2.3. Deep Space Missions with Separatable Transfer Module.

In some missions, multiple small satellites are carried together with a primary spacecraft or even a dedicated transfer module over a long distance. Small satellites will separate from the primary spacecraft when they reach their designated orbit to continue their tasks.

Launched in 2018, BepiColombo is a collaborative mission of the European Space Agency (ESA) and the Japanese Space Agency (JAXA) to study Mercury and its environment using two Mercury satellites, the ESA’s Mercury Planetary Orbiter (MPO) and the JAXA’s Mercury Magnetospheric Orbiter (MMO) [17]. The MPO has a dry weight of 1080 kg and is equipped with a chemical propulsion system for attitude and orbital control, whereas the MMO is a much smaller satellite with no propulsion system. The two small satellites are carried to their destination by the mercury transfer module (MTM). The entire spacecraft weighed about 4000 kg at launch. The MTM has both chemical and electric propulsion systems. The main engines are four 145 mN ion thrusters [18]. The electric propulsion system has the $I_{sp}$ of more than 4000 s, allowing the satellites to carry as many scientific instruments as possible, but the tradeoff is a 7-year journey due to the relatively low thrust level. The MTM will have to perform several swingbys before it reaches Mercury’s orbit.
This configuration allows for missions with multiple objectives or international collaboration. Without the need for orbital transfer, the small satellites can integrate micropropulsion systems to complete the tasks.

3. Micropropulsion Technology

Packing the propulsion system into modules can greatly reduce the complexity of the design, manufacturing, and testing processes, lowering the technical threshold and promoting cooperation. In this section, 3 types of micropropulsion modules developed by BICE are introduced, and all of them have passed flight tests.

3.1. Solid Cold Gas Micropropulsion Module Technology. Formation flight, station keeping, and other tasks of micro/nanosatellites necessitate a propulsion system with low power consumption, modular design, and plug-and-play installation. A high performance solid cold gas micropropulsion module has been developed. The 1 U model has a mass of 1.2 kg and provides a total impulse of more than 100 Ns. The 0.7 U model weighs 640 g and has a total impulse of more than 30 Ns. The maximum power consumption is less than 1.5 W, and the standby power is less than 50 mW. The gas-producing efficiency of a single gas generator is greater than 45 percent.

In the solid cold gas micropropulsion module, the propellant is stored at normal pressure in the form of a solid substance, and the gas is generated only when needed. During the gas generation process, the control and drive circuit triggers the ignition of the cold gas generator, and then, high temperature gas is generated to set fire to the solid substance to produce high pressure nitrogen in the gas chamber. When an impulse is needed, the valve of the thruster is opened to produce the desired thrust. The pressure in the gas chamber is kept within a certain range. When the pressure is less than a threshold, the system triggers the next gas generator to ignite and produce gas.

The solid cold gas micropropulsion module consists mainly of the control-drive circuit, solid cold gas generator unit, pressure transducer, temperature transducer, and cold gas thrusters (shown in Figure 4). It communicates
with the computer of the satellite via the I²C or CAN port. The number of thrusters is customizable. The number of generators can also be adjusted to meet the requirements of various missions.

The 0.7 U solid cold gas micropropulsion module has 12 generator units. The performance indices for it are listed in Table 1. The module can be expanded based on the current interface. The total impulse of 1 U solid cold gas micropropulsion module can reach 100 Ns, and the weight is 975 g.

The diameter of the generator for the 0.7 U model is 18.4 mm, and the height is 30 mm. The weight of nitrogen produced by a single generator is 3.85 g. The thruster operates in the pressure drop mode. When the first generator ignites, the pressure of gas chamber is boosted to 1.5 MPa. The maximum thrust is 50 mN. When the pressure drops to 0.1 MPa, the thrust is 3.0 mN, and the second generator prepares to ignite.

Thrust calibration is performed for the solid cold gas micropropulsion module. Data were measured for pressure values of 0.2 MPa, 0.4 MPa, 0.6 MPa, 0.8 MPa, 0.9 MPa, and 1.0 MPa, respectively. As is demonstrated in Figure 5, the thrust error is less than 5%, indicating that the thrusters’ performance is consistent. Such a propulsion module was carried by the DFH micro-nanotechnology experiment satellite in 2018 and successfully performed formation control with multiple satellites.

3.2. ADN-Based Nontoxic Micropropulsion Technology. The monopropellant propulsion module consists of cold gas generators, an exhaust valve, a gas chamber, a fuel tank, pressure sensors, temperature sensors, and four 200 mN high performance thrusters. Figure 6 depicts the propulsion module schematically, and the structure of the module is shown in Figure 7. The ADN-based monopropellant is a mixture of

![Figure 6: The diagram of the ADN monopropellant module.](image)

![Figure 7: The structure of the ADN monopropellant module.](image)

![Figure 8: 200 mN ADN thruster ignition test.](image)
three components: ammonium dinitramide, methanol, and water. It is nontoxic and has a high density, a low freezing point, low volatility, and high stability. It has the advantage of not requiring any special safeguards during the storage and handling processes.

The micro monopropellant propulsion module is pressurized by the solid cold gas generation technology inherited from the solid cold gas micropropulsion module. After launched into orbit, the control circuit activates the gas generator to pressurize the tank with nitrogen. When the tank pressure falls below a certain level, the circuit switches to the next generator, which can keep the pressure high.

For the 200 mN thruster, the propellant was regulated by capillary and then injected into the combustion chamber. In order to prevent the bubbling in the capillary, some thermal measures are implemented in the injector to reduce the temperature on the capillary. The thruster were tested under continuous and pulsed operation mode [19], as shown in

![Figure 9: The temperature and thrust curves of 100 s steady-state operation.](image)

![Figure 10: The temperature and thrust curves of ON/OFF 100 ms/400 ms pulsed operation.](image)
Figure 8. The pressure and temperature curves are shown in Figures 9 and 10. The thruster also passed a 3000 s steady-state test and a 10000-cycle pulse test. The specific impulse is 205 s for steady-state. The maximum wall temperature of the combustion chamber is about 1000°C, and the temperature of the injector is below 130°C during the operation. The module weight is about 1.3 kg, and the total impulse is about 850 Ns. In 2019, the ADN micropropulsion module successfully completed a flight test on the Ningxia-1 satellite.

3.3. Microcathode Arc Micropropulsion Module Technology. The μCAT, firstly developed by the George Washington University’s (GWU) Micropropulsion and Nanotechnology Lab, is based on the physical phenomenon of vacuum (cathodic) arcs [9, 20]. In 2019, BICE built μCAT micropropulsion modules for Tianqin-1 and for other small satellites. The micropropulsion module has a PPU and thruster assemblies (shown in Figure 11). The firing of a μCAT is shown in Figure 12. The PPU generates pulsed high voltage (several hundred volts) to create an arc between an anode and a metal cathode, causing evaporation and ionization of cathode material. The plasma is then expelled from the arc source to produce the thrust. The 0.3 U (100 mm × 100 mm × 30 mm) module’s weight is about 350 g, and the total impulse is greater than 100 Ns. The power consumption module is less than 10 W. The average thrust is adjustable to up to a few tens of micro-Newton by varying the repetition rate of the pulsed arc. Because the CAT module contains no pressurized parts, the manufacturing process is much simpler when compared to other propulsion systems that use a gas medium.

4. New Developments for Interstellar Missions

4.1. Solar System Boundary Exploration. Many interplanetary probes have been successful, including the well-known Messenger, Cassini, and New Horizons. Investigations of the solar system boundary have become the frontier of astrophysics. China has proposed a mission to investigate the nose and tail of the heliosphere (shown in Figure 13), which is the boundary between the interstellar medium and plasma that originated from the sun. A pair of probes are planned to launch around 2024 and then fly across a distance of 80 to 150 Au before arriving at the heliosphere around 2049 [21].

The mission is significant since the edge of the heliosphere has not been fully explored by mankind. The physical property of the boundary remains unknown. The mission has a few objectives [21, 22]. The first one is to map the entire structure of the heliosphere. The spreading and evolution of solar wind on the heliosphere and the interaction of solar wind with interstellar wind have not been resolved. Scientists are not able to predict the shape of the heliosphere and the motion of its boundary. The second aim is to investigate the history of the solar system. The interplanet dust
reveals the abundance of isotopes at the beginning of the solar system. The celestial bodies in the Kuiper belt are primeval objects where clues about the early solar system are likely to be discovered.

4.2. Electric Sail for Solar System Boundary Exploration. Propellant-free propulsion is under development for future missions. Electric sail (also known as HERTS, Heliopause Electrostatic Rapid Transport System) is a prospective technology for future deep space exploration [8, 23]. As the Chinese spacecraft approaches the solar system boundary, it will release two small satellites, one of which will have an electric sail. As is shown in Figure 14, the electric sail has many long and thin wires or so-called tethers, extending from its center. The tethers are charged to thousands of volts, creating high potential regions around them to deflect protons. The device generates thrust by momentum exchange with the photons, and it functions as a virtual sail propelled by the solar wind. Electrons are constantly absorbed by the wires, and an electron gun serves as a neutralizer. Thrust vectoring for attitude control can also be realized by adjusting the potential of the wires individually. Because electric sails do not require propellant, they are ideal for long-term deep-space missions.

Unlike the solar sail, which is primarily driven by photons striking its limited surface area, the electric sail tethers are more than 10 km long and have an effective radius of about 10 meters. Another issue with the solar sails is that their thrust decreases dramatically as the photon flux with increasing distance from the sun (decays as $1/r^2$), making them unsuitable for outer solar system travel, whereas the thrust of electric sails decays as $(1/r)^{7/6}$ inside the termination shock [24].

In addition, the electric sail functions as a particle probe. For China’s solar system boundary exploration, the electric sail will have 100 wires with the length of 126 km, and each will be charged to 1000 V. With this configuration, at 1 A.U. from the sun, electric sail is expected to provide 1 N thrust, and at the solar system boundary however, the properties of the space medium have yet to be detected. As the spacecraft approaches the termination shock, where the solar wind abruptly decelerates from supersonic to subsonic, the thrust of the electric sail is expected to drop dramatically. The force and current on the electric sail will provide valuable data for heliosphere research. On the other hand, at 100 A.U. from the sun, the plasma density is 4 orders of magnitude lower than in Earth’s orbit, making it difficult to detect with conventional charged particle detectors.

BICE has implemented an electric sail prototype (shown in Figure 15), consists of wires, an electron gun, and expansion mechanism. Its expansion mechanism is capable of expanding four 3-meter-long wires. The charge voltage is set at 1000 volts. A plasma thruster was fired in front of the electric sail to measure the thrust. On-orbit thrust of the prototype is approximately 10 N.

5. Summary

In this paper, the selection of propulsion systems for deep-space exploration was discussed, primarily using examples from China. For lunar exploration, both Queqiao and Longjiang were equipped with monopropellant systems but with different thrust levels, as Longjiang’s mass is about an order of magnitude lower than Queqiao’s. For Tianqin-1, a pathfinder for the gravitational wave detection, realizing drag-free control, is essential, so cold gas thruster and μCAT were chosen to provide μN-level variable thrust. The new micro-propulsion modules, which are perspective propulsion systems for small deep space platforms, were then introduced. The solid cold gas propulsion module, the ADN monopropellant micropropulsion module, and the μCAT propulsion module were developed by BICE. For a future solar system boundary exploration mission of China, a small probe with an electric sail propulsion system was proposed. The electric sail not only serves as a propellant-free thruster but also

![Figure 15: Prototype electric sail: (a) main structure; (b) electron gun.](image-url)
functions as a detector probing the properties of the space medium.

**Data Availability**

The data is freely available from corresponding author upon request.

**Conflicts of Interest**

The authors declare that there is no conflict of interest regarding the publication of this article.

**Authors’ Contributions**

Yanming Wei is responsible for overall coordination, supervision, and investigation of deep space missions. Hao Yan is responsible for manuscript writing. Xuhui Liu is the supervisor of the micropropulsion technology. Yang Yu provides technical support for the electrical sail preliminary study. Jinyue Geng, Tao Chen, Tuqou Fu, Gaoshi Su, Yu Hu, and Daoman Han provide technical support for propulsion systems or modules.

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