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Research and Development of the Small LOX/Methane Propulsion System for an Experimental Reusable Winged Rocket WIRES#015

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Abstract

LOX/Methane engines have been researched in Japan since the early 2000s, and the combustion tests of 30kN class full-expander cycle engine has been succeeded in 2021. The engine will be installed in the WIRES#015 (Winged Reusable Sounding rocket) and be demonstrated in the first flight in 2025 under a collaborative research contract with the Tokyo University of Science. To operate the engine, the vehicle needs a propulsion system, including tanks, propellant supply units, electrical control units and engine gimbaling units. Research and development on the propulsion system are proceeding, and its status is described in this paper.

1. Introduction

1.1 Introduction

Liquid hydrogen and kerosine are common rocket propellants. Liquid methane is superior to liquid hydrogen because it is easier to store in space. It is also safer because the risk of leakage and explosion is low. In addition, liquid methane provides better fuel performance (specific impulse) than kerosene. For these reasons, methane propulsion systems are expected to be used increasingly in future rockets and inter-orbit transport vehicles. Therefore, R & D has been conducted in the United States and Europe since around 2000.

Figure 1 shows the roadmap of JAXA's R&D on methane engine propulsion systems. The work on methane engines, the main components of methane propulsion systems, began in 2003, and has progressed to feasibility studies. Since 2013, we have also been researching a regenerative cooling combustion chamber with the goal of a high specific impulse [1-4]. In 2021, we almost completed the feasibility study by demonstrating the world's top level specific impulse through a combustion test using an engineering model engine (almost the same as the flight configuration) [6]. As the next step, by building the propulsion system utilizing a methane engine on an experimental vehicle, the WIRES#015, and conducting flight demonstrations, we will clarify any issues affecting the installation of a methane propulsion system and gain familiarity with its operation, such as optimal chill-down and safety management.

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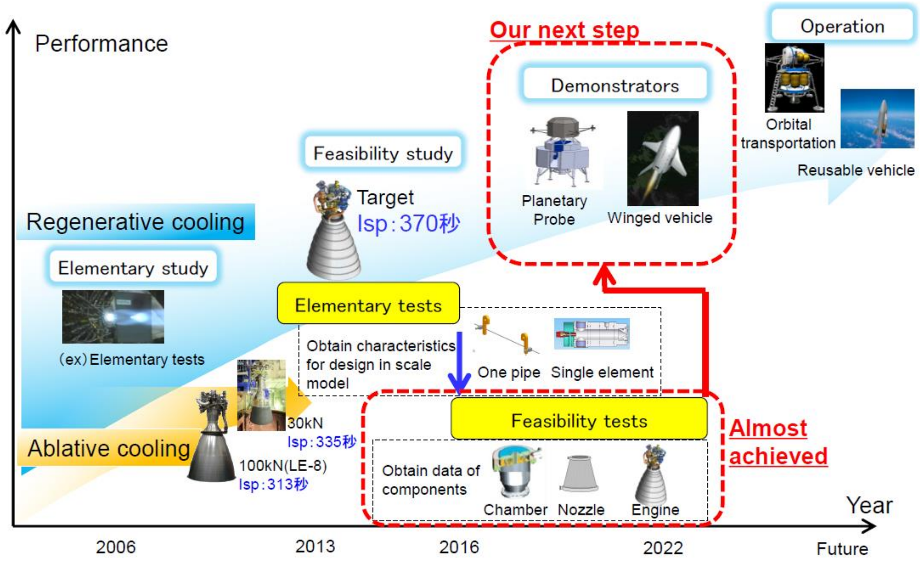
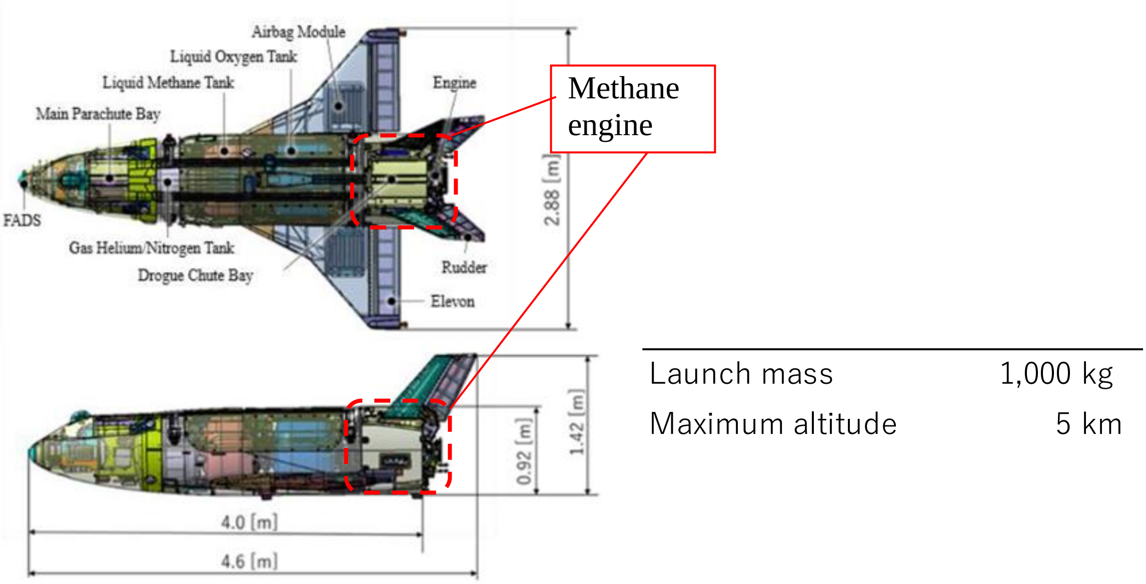


Figure 1: Our strategy roadmap for methane propulsion's R&D

1.2 Cooperation between JAXA and TUS on WIRES#015

WIRES#015 is a winged experimental vehicle for demonstrating a future spaceplane's methane propulsion system and sub-orbital flight technology. It is undergoing collaborative research with Tokyo University of Science (TUS). Figure 2 shows an overview and the main specifications. The flight plan of WIRES#015 starts from the powered ascent phase, with the methane engine firing for about 30 seconds, which brings the vehicle to an altitude of about 5km. After the powered ascent, the vehicle will glide toward the target point, and perform a soft landing with parachutes and airbags (Figure 3). One proposed launch site is the Esrange Space Center in Kiruna, Sweden. JAXA is mainly responsible for developing and operating the propulsion system, while TUS is developing other sub-systems and ground facilities and coordinating launch campaigns. The flight of WIRES#15 will be in 2025[5].



Launch mass	1,000 kg
Maximum altitude	5 km

Figure 2: Summary and WIRES#015 specifications[5]

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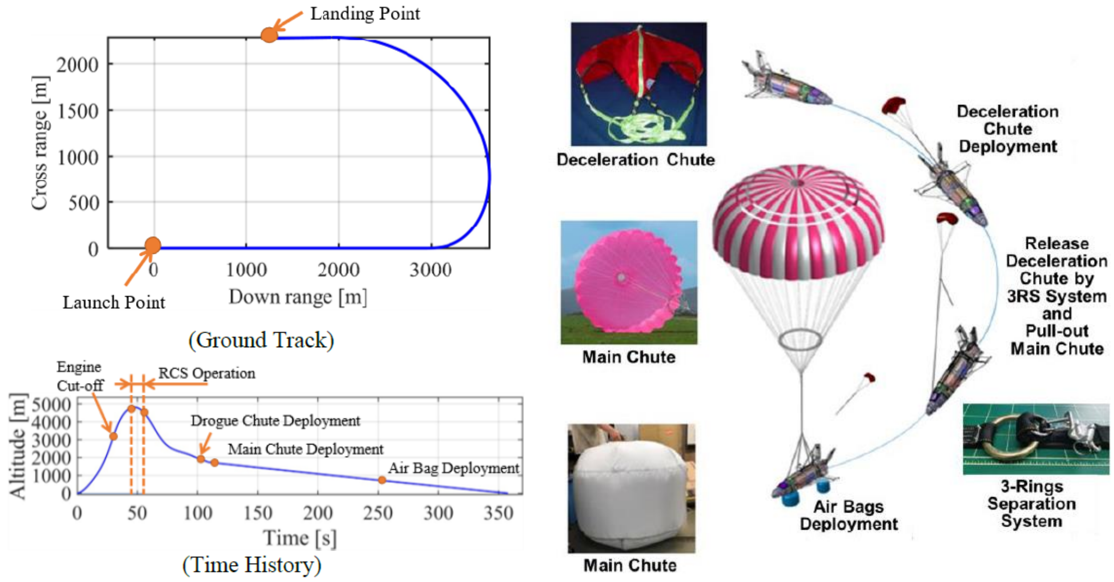


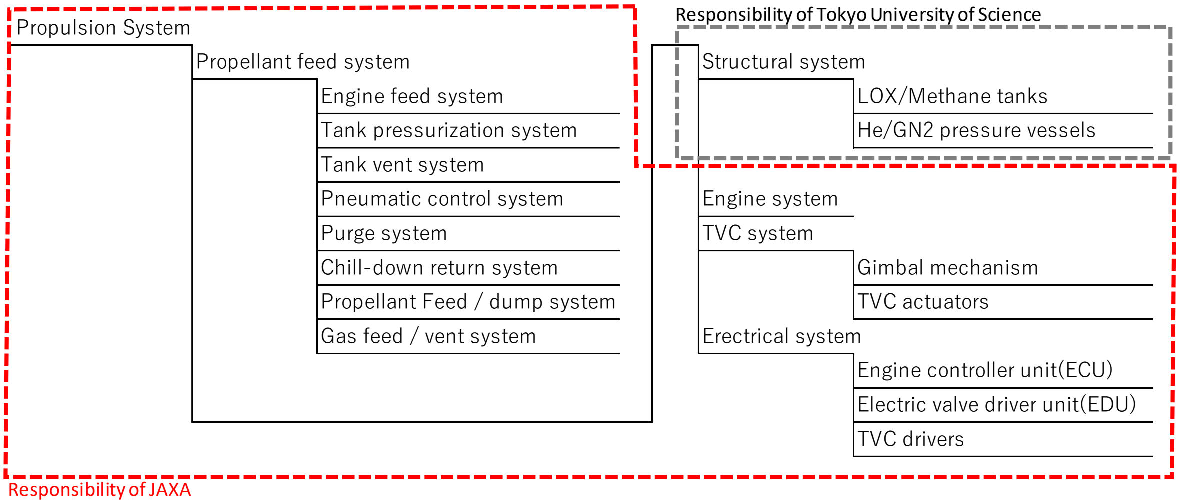
Figure 3: Summary of WIRES#015's flight plan (orbit and recovery system)[5]

1.2 Summary of propulsion system of WIRES#015

The main function of the propulsion system is to supply liquid oxygen (LOX) oxidant and liquid methane fuel to the engine under the specified conditions to generate the required thrust. Figure 4 shows the main component list of the WIRES#015 propulsion system. Figure 5 shows the external view of the propulsion system.

JAXA is responsible for integrating the propulsion system, including system design, assembly, and operation, and is also responsible for providing the pressurized-gas propellant feed system, engine system, Thrust Vector Control (TVC) system, and related electrical units. TUS is developing tanks and gas pressure vessels.

Since the main aim of JAXA is to demonstrate the flight of the methane propulsion system under low-cost and rapid development, we use ready-made or consumer products as often as possible.



- Propulsion System
  - Propellant feed system
    - Engine feed system
    - Tank pressurization system
    - Tank vent system
    - Pneumatic control system
    - Purge system
    - Chill-down return system
    - Propellant Feed / dump system
    - Gas feed / vent system
  - Structural system
    - LOX/Methane tanks
    - He/GN2 pressure vessels
  - Engine system
  - TVC system
    - Gimbal mechanism
    - TVC actuators
  - Erectrical system
    - Engine controller unit(ECU)
    - Electric valve driver unit(EDU)
    - TVC drivers

Figure 4: Main component list of the propulsion system

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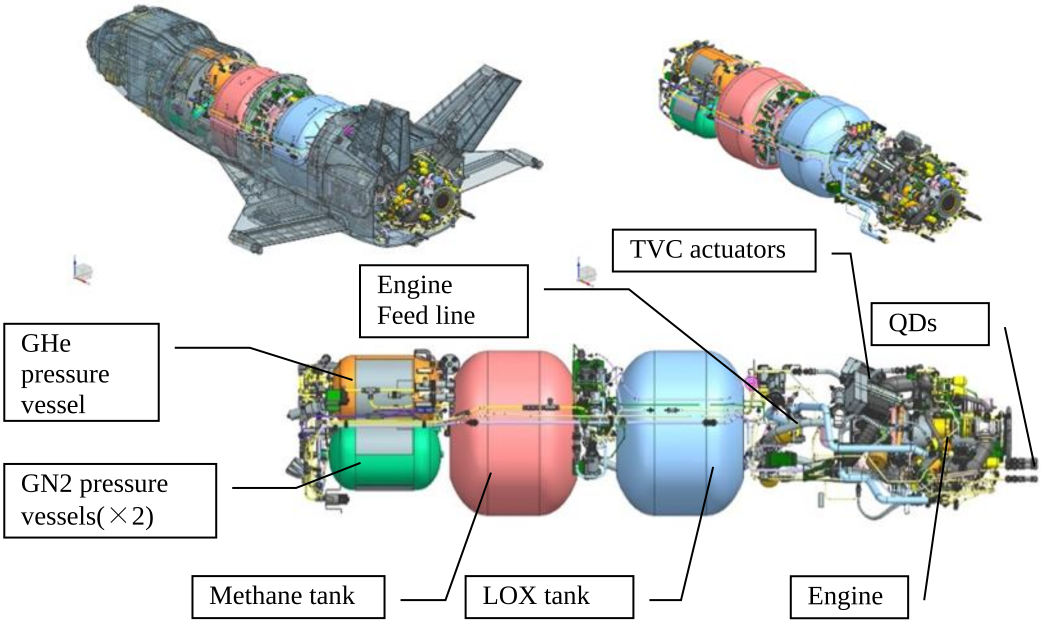


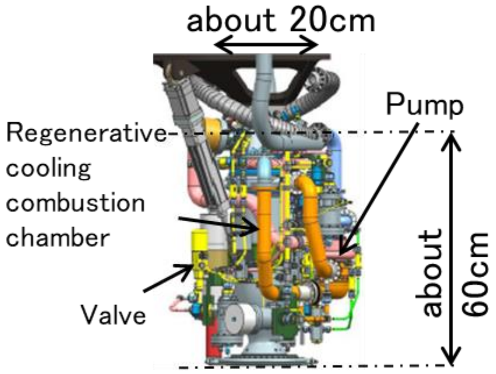
Figure 5: External view of the propulsion system

2. Status of propulsion system development

2.1 Engine system

The installed engine is the test model, which is almost the same as the flight configuration (Figure 6), and was used to demonstrate the world's top level specific impulse in the 2021 combustion test[6]. The chill-down and the main propellant valves are electrically operated with a special toggle mechanism, that provides flow control and shutoff functions with one valve[2][7]. The turbopump is a single-shaft type built mostly with 3D printers[8].

Mainly to coordinate the operating point, we carried out additional firing tests for about 130 seconds from February to March 2023(Figure 7), confirming the performance, so we were sure the engine became ready to be installed. The expansion ratio is smaller than that for the optimum expansion conditions under sea level because the possibility of throttling operation was assumed at the beginning of the WIRES#015 project.



Thrust	15.84 kN
Mixture ratio	2.99
ISP	224 s※
Expansion ratio	4.4

(※ without extension nozzle under sea level condition)

Figure 6: External view and specifications of installed methane engine

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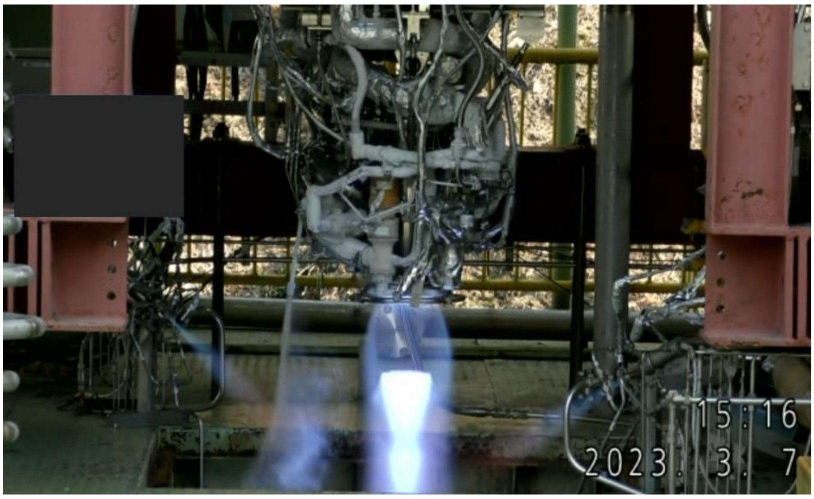

Figure 7: Firing test of installed engine in 2023

2.3 Propellant feed system

The primary function of the propellant feed system is to pressurize the gas in the tank and supply liquid propellant to the engine at a specified flow rate. This vehicle’s LOX/Methane tanks are pressurized with helium gas from the pressure vessel. Figure 8 shows the basic configuration of the system. In the design of the pressurized supply system, it is important to evaluate (1) pressure loss from the tank to the engine and (2) pressurization characteristics in the gas phase (the “collapse factor”). Pressure loss due to internal tank device, which have particularly large uncertainty, have been roughly determined by TUS liquid flow tests using an Engineering Model (EM) tank by TUS. The collapse factor is assumed based only on the experience of previous project test data. Thus, it should be validated by tests with an EM tank as soon as possible. In evaluating the system feasibility of propellant feed system by dynamic pressurization simulation using the current characteristic values, the temperature of the helium gas was found to decrease to about -40°C due to polytropic expansion, a temperature below the allowable lower limit of the pressure regulator between the pressure vessel and tank. Essentially, the reason was that the vessel’s initial pressure is set to too high (approximately 60 MPa), with priority given to compactness because of limited space in a small vehicle. we are considering heating the pressure vessel until just before the lift-off to meet the temperature specification with a ready-made pressure regulator. We plan to carry out the liquid flow test and the Captive Firing Test (CFT) in 2024 for the final verification of the operation and characteristics of the pressurized-gas propellant feed.

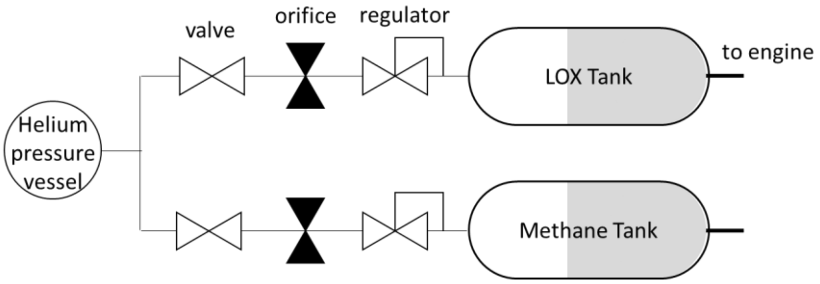

Figure 8: Base configuration of propellant feed system (tank pressurization system and engine feed system)

Unlike expendable rockets, this vehicle is expected to be recovered after landing. To ensure the safety of the workers in recovery operation, the followings are required: (1) prohibiting personnel from approaching the vehicle before the liquid propellant evaporates, meaning that the QDs for external power/gas supply cannot be connected for about 3 to 30 hours.) and (2) two fail-safes against hazards during personnel approach. Regarding (1), in preparing for exhausted purge gas for the turbopump while waiting for evaporation to complete, shutoff valves between the tank and engine reduce the risk of explosion due to excessive LOX mixed with methane in the turbopump (see Figure 9). As for (2), for example, the hazard of bursting due to excessive pipeline pressurization is controlled by redundant valves such as safety valves in each pipeline (see Figure 10).

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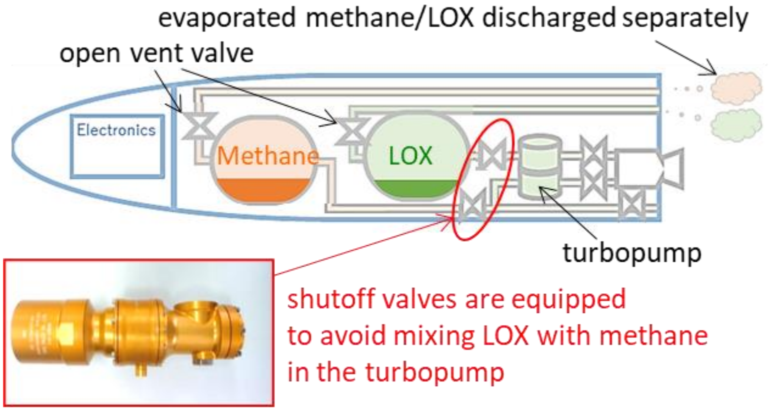

Figure 9: Operation of liquid propellant evaporation and electrical shut-off valve

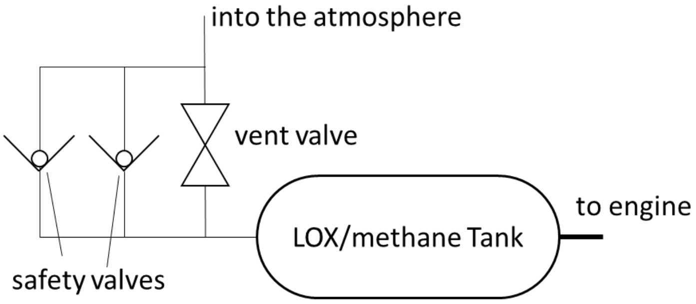

Figure 10: Example of safety design for excessive tank pressurization

2.5 TVC system

To support attitude control by aerodynamic control surfaces (elevon and rudder) for the powered ascent, WIRES#015 has a Thrust Vector Control (TVC) system for gimbaling the engine up to 5° in pitch and yaw (see Figure 11). To reduce development costs for the device of generating force for gimbaling, we adopted a commercial electric actuator/driver. To use the ready-made actuator, the following activities were implemented. To verify the performance of the specifications shown by the manufacturer, we carried out an elementary actuator test (Figure 12). For the sliding parts of the gimbal mechanism (with cross shaft) of the engine, ball bearings were adopted because they placed smaller load on the actuators than sliding bearings, and they were confirmed in the combustion test in Section 2.1 to be durable against the thrust and vibration load of the engine. A gimbal response dynamic model, including the actuator performance specifications, fitting position, and engine mass characteristics, was implemented in MATLAB code, which is incorporated into the flight analysis of the vehicle, through which we finally obtained the prospect of attitude control. To protect the motor and ball screw inside the actuator from landing impact, the actuator will be extended to a mechanical stop at the landing so that the load is carried by the outer casing instead of the inside of the actuator (Figure 13).

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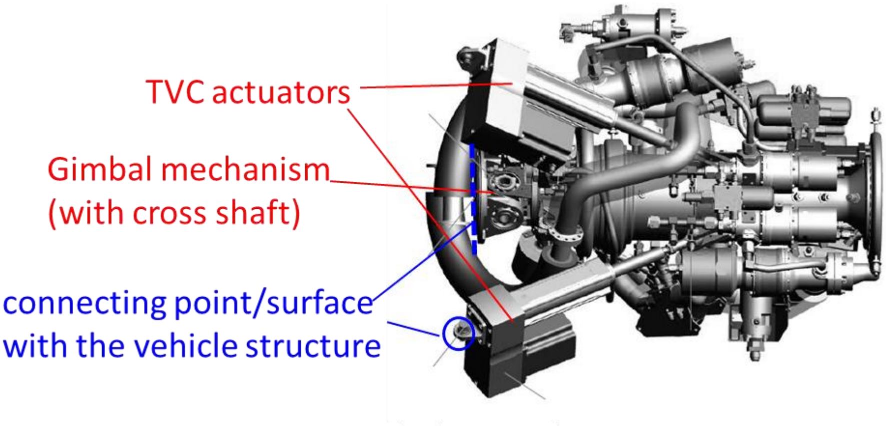

Figure 11: External view of TVC system (view from above the vehicle)

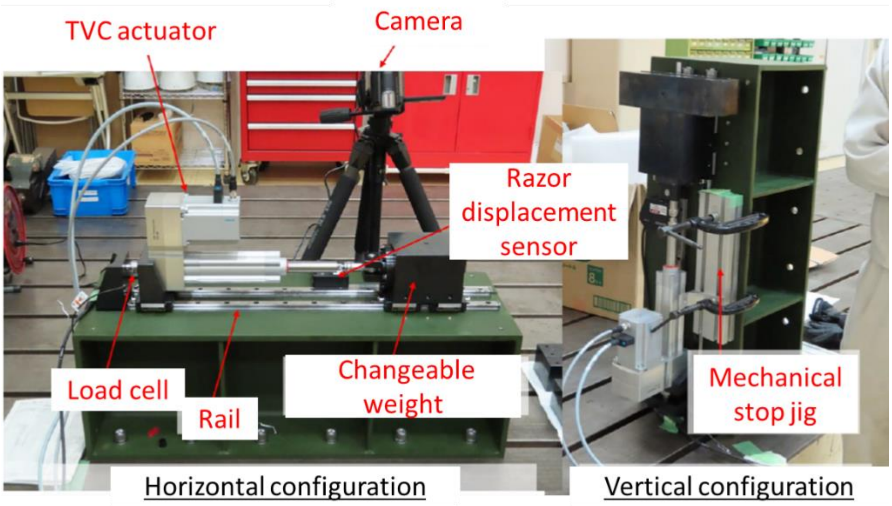

Figure 12: Elementary test of the actuator for TVC\

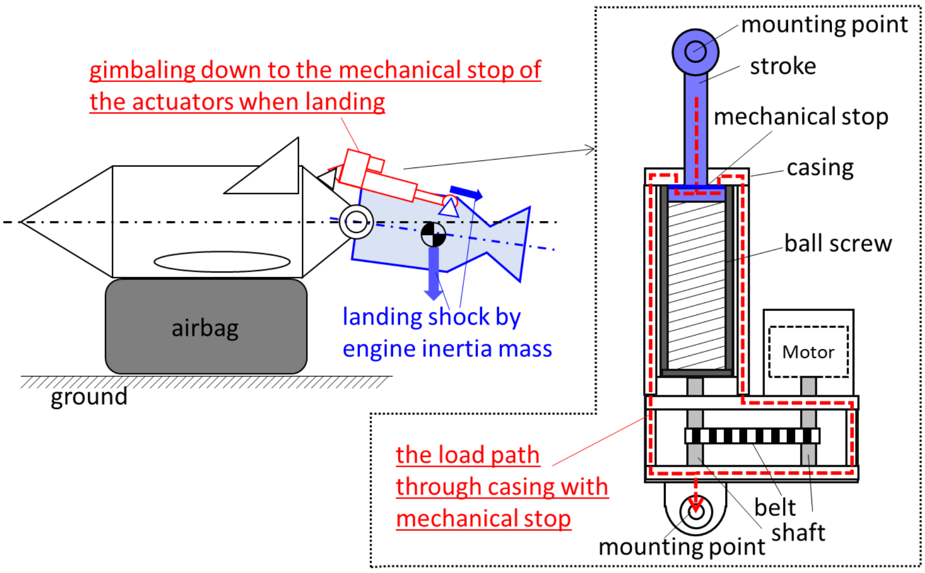

Figure 13: Operation of TVC at landing

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2.6 Electrical equipment of propulsion system

Figure 14 shows the electrical system and functional overview of the propulsion system. Figure 15 shows the external view of Engine Controller Unit (ECU) and Engine Driver Unit (EDU), which are the main electrical units of the propulsion system and are mounted on the avionics bay in the head of the vehicle.

ECU is the central controller of the propulsion system. Triggered by commands from the vehicle's avionics system (including flight safety commands), the ECU starts and stops engine combustion by operating valves and exciters according to a scheduled sequence. In addition, before and after the flight, the ECU opens and closes the necessary valves at any time according to ground commands. All measurement data related to the propulsion system are aggregated, recorded in the ECU, and transferred to the vehicle's avionics computers. The necessary data for operation are downlinked through telemetry.

The EDU is an electrical package of six electrical valve driver boards for six valves. In addition to controlling the electrical valves based on the degree-of-opening command from the ECU, the EDU can preferentially receive an emergency engine shutdown command to close the main propellant valves from the emergency system computer for flight termination procedures.

As described in Section 2.3, electrical power cannot be supplied from outside long after landing. Therefore, to save internal battery power usage, we plan to intermittently turn on the propulsion system's power (Figure 16).

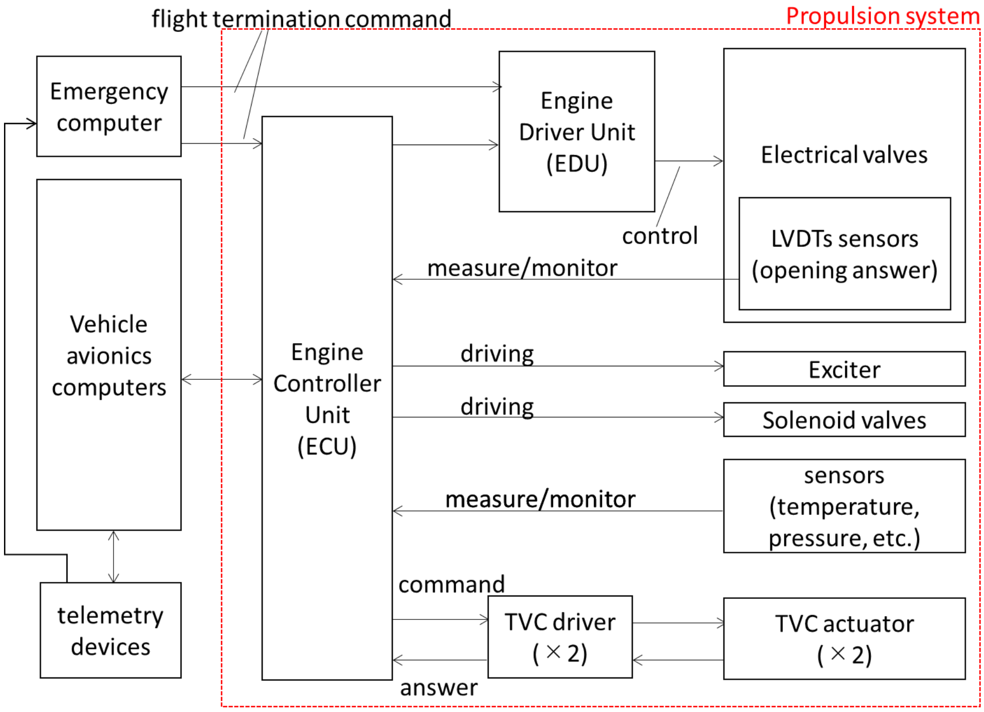

Figure 14: Electrical configuration of propulsion system (excluding power supply line)

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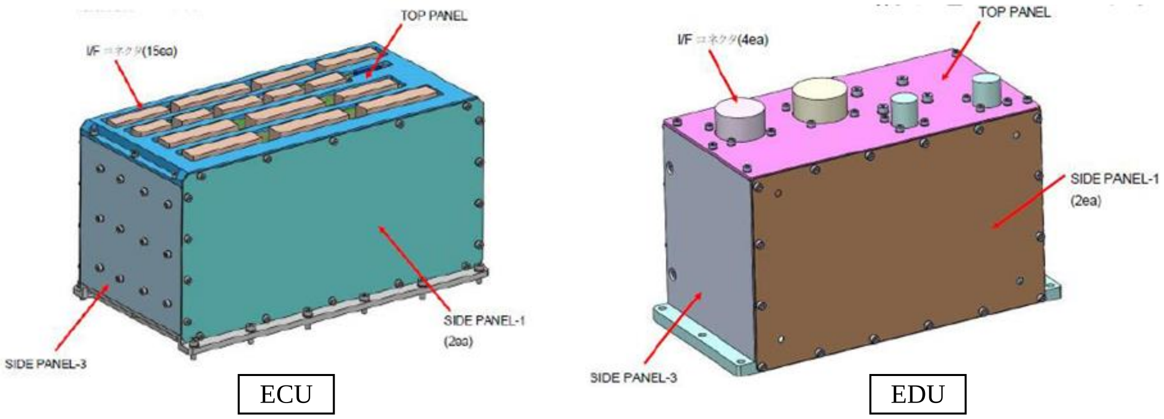

Figure 15: External views of ECU and EDU

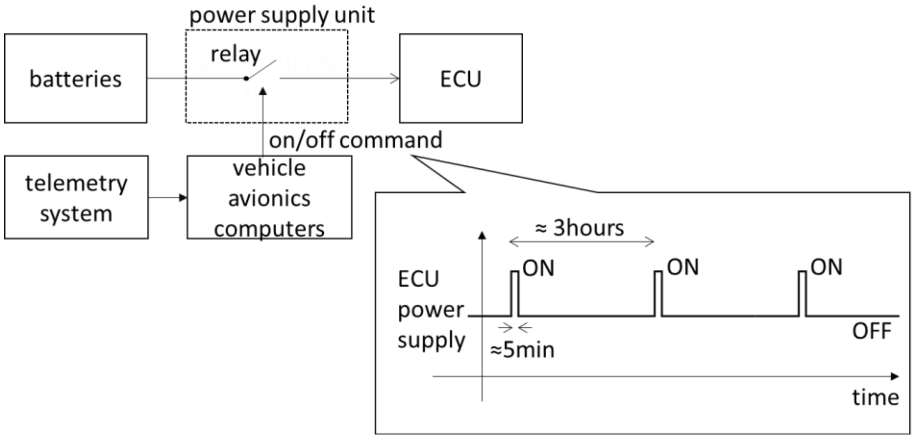

Figure 16: Power ON/OFF operation of ECU while waiting for liquid propellant evaporation after landing

2.7 Mounting design

The overall mounting design of WIRES#015 was challenging because it is a small vehicle. Especially when it comes to the propulsion system, the mounting around the engine was difficult. The QDs interface with the ground equipment are passively separated when the vehicle lifts off, so they had to be mounted at the rear of the fuselage, and their pipeline had to be routed around the engine. Further, an RCS pipeline is installed at the rear of the fuselage. To avoid interference with the engine gimbal freedom of movement of 5° (see Figure 17), we finally decided to make a small bulge at the rear of the fuselage.

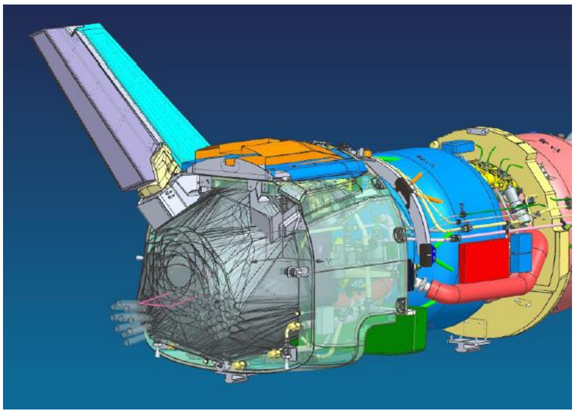

Figure 17: Interference check of the engine with gimbaling by using CAD model

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3. Conclusion

To realize the flight demonstration of small LOX/Methane engine, a 30kN class full-expander cycle engine was designed, manufactured, and verified in the firing tests. Further, the WIRES#15 propulsion system, which feeds the propellants to the engine, was investigated under a cooperative research agreement with the Tokyo University of Science. The design feasibility of the engine and propulsion system was confirmed, as described in this paper, and the detailed design is proceeding. After finalizing the design of the whole vehicle, including the propulsion system, in 2023, the vehicle's components will be procured and assembled. Following the system tests of the vehicle, the maiden flight of WIRES#15 will be made in 2025.

Acknowledgments

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