Progress of Subscale Winged Rocket Development and Its Application to Future Fully Reusable Space Transportation System

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ABSTRACT

Kyushu Institute of Technology has been studying unmanned suborbital winged rocket called WIRES (WInged REusable Sounding rocket) and its research subjects concerning aerodynamics, NGC (Navigation, Guidance and Control), cryogenic composite tanks etc., and conducting flight demonstration of small winged rocket since 2005. WIRES employs the original aerodynamic shape of HIMES (HIghly Maneuverable Experimental Sounding rocket) studied by ISAS (Institute of Space and Astronautical Science) of JAXA (Japan Aerospace Exploration Agency) in 1980s. This paper presents the preliminary design of subscale non-winged and winged rockets called WIRES#013 and WIRES#015, respectively, that are developed in collaboration with JAXA, USC (University of Southern California), UTEP (University of Texas at El Paso) and Japanese industries. WIRES#013 is a conventional pre-test rocket propelled by two IPA-LOX (Isopropyl Alcohol and Liquid Oxygen) engines under development by USC. It has the total length of 4.6m, and the weight of 1000kg to reach the altitude of about 6km. The flight objective is validation of the telemetry and ground communication system, recovery parachute system, and launch operation of liquid engine. WIRES#015, which has the same length of WIRES#013 and the weight of 1000kg, is a NGC technology demonstrator propelled by a fully expander-cycle LOX-Methane engine designed and developed by JAXA to reach the altitude more than 6km. The flight tests of both WIRES#013 and WIRES#015 will be conducted at the launch facility of FAR (Friends of Amateur Rocketry, Inc.), which is located at Mojave Desert of California in United States of America, in May 2018 and March 2019 respectively. After completion of WIRES#015 flight tests, the suborbital demonstrator called WIRES-X will be developed and its first flight test well be performed in 2020. Its application to future fully reusable space transportation systems, such as suborbital space tour vehicles and two-stage-to-orbit launch vehicle, is discussed.

KEYWORDS: *reusable space transportation, unmanned winged rocket*

NOMENCLATURE

Uppercase Letter

ADS - Air Data Sensing
ARINC - Aeronautical Radio INC.
AOA - Angle of Attack
CAMUI - Cascaded Multistage Impinging-jet
CFRP - Carbon Fiber Reinforced Plastic
COTS - Commercially Off The Shelf
EM - Engineering Model
FAR - Friends of Amateur Rocketry
GFRP - Glass Fiber Reinforce Plastic
GHe - Gaseous Helium
GPS - Global Positioning System
GSE - Ground Support Equipment
IHI - Ishikawa Heavy Industries
IPA - Iso Propyl Alcohol
INS - Inertial Navigation System
ISAS - Institute of Space and Astronautical Science
JAXA - Japan Aerospace Exploration Agency
LOX - Liquid Oxygen
LCH4 - Liquid Methane
NGC - Navigation, Guidance and Control
OF - Oxidizer to Fuel
RCS - Reaction Control System
TSTO - Two Stage To Orbit
USC - University of Southern California
UTEP - University of Texas at El Paso
WIRES - WInged REusable Sounding rocket

1 INTRODUCTION

The need for reusable space transportation has evolved all around the world to facilitate space travel with low launch cost. Many organizations are developing reusable space planes. The successful demonstration of Spaceship One, a reusable suborbital vehicle by Scaled Composites is a prime example. However, a mother vehicle and complex ground equipment were utilized. Authors aim to develop simple single stage reusable suborbital vehicles. Since 2005, Kyushu Institute of Technology (Kyutech), Japan is developing unmanned suborbital winged rocket called WIRES (WInged Reusable Sounding rocket) as a research project towards future fully reusable space transportation [1, 2]. WIRES employs the original aerodynamic shape of HIMES studied by ISAS of JAXA in 1980s [3, 4]. Winged rocket is one of the ideal types of space transportation system due to its high potential of reusability, operational flexibility and abort capability. All the necessary technologies demonstrated in the WIRES rocket will be employed to develop the future reusable space transportation systems. Currently, three experimental vehicles are in operational phase (WIRES#014-3) and design phase (WIRES#013 and #015) as shown in Fig.1.

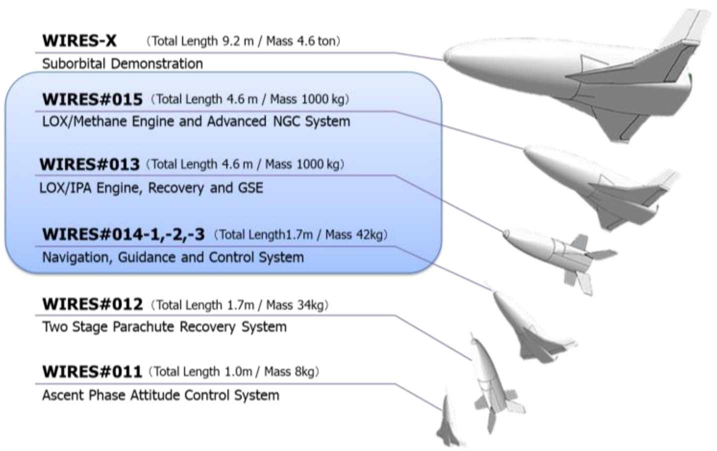

Figure 1: Development road map of winged rocket “WIRES”

Since 2012, Kyutech has been developing WIRES#014, which has a total length of 1.7 m and a weight of 42kg. The objective of this vehicle is to demonstrate the preliminary technology of onboard autonomous NGC system in collaboration with JAXA. During the development of WIRES#014, three variants have been fabricated with improvement in each subsystem. For WIRES#014-1, the structure had a skin, longeron and frame and employed CAMUI hybrid rocket engine of Hokkaido University. The flight test was conducted in 2013, but failed its controlled flight due to the malfunction of ADS system. Next WIRES#014-2 was fabricated and had a semi-monocoque structure reducing the structural weight without any loss of strength and employed a simpler COTS hybrid rocket engine Hypertek M1000. However, during the ground combustion in 2014, the vehicle was lost due to the unexpected explosion. Finally in 2015, authors have fabricated WIRES#014-3, made additional reinforcement to the Hypertek M1000 nozzle which caused the previous explosion. The flight test was conducted and the vehicle was successfully recovered using the two stage parachute system. Fig.2 shows the validation test of all the three variants of WIRES#014.

Figure 2: Validation test of WIRES#014-1,-2,-3

Currently, to validate the reusability and rectify minor issues from the previous flight test, WIRES#014-3A is under final development phase and will be launched in October, 2017. In this paper, authors will discuss the preliminary design of WIRES#013 and WIRES#015 [5, 6, 7] developed in collaboration with the member institutions of Future Rocket Research Consortium (Fig.3), such as JAXA, Kawasaki Heavy Industries Ltd., IHI, IHI Aerospace, Toray Carbon Magic Inc., Chugoku Kogyo Ltd., PD Aerospace Ltd. and Xenocross Corporation. USC and UTEP are also working with this consortium in the development.

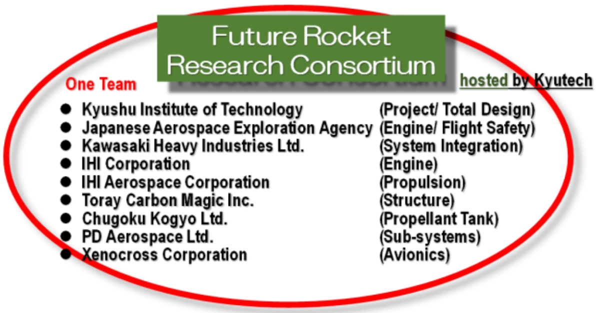

Figure 3: Organization of Future Rocket Research Consortium

2 PRELIMINARY DESIGN OF WIRES#013 AND WIRES#015

2.1 Mission objectives and major specifications

WIRES#013 is a non-winged rocket propelled by two IPA-LOX engines of total 20kN thrust provided by USC as the pre-test rocket for the winged WIRES#015. It has the total length of 4.6m and the weight of 1000kg to reach the altitude of about 6km. There is no active control system in this vehicle. The mission objectives are as follows:

- Telemetry and ground communication system;
- Ground support equipment;
- Recovery system using 2 stage parachutes and airbags;
- Validation of LOX and IPA engine.

The major specifications are presented in Table 1.

Table 1: Major specifications of WIRES#013

Specifications	Value	Unit
Total Length	4.6	[m]
Body Length	4.0	[m]
Body Diameter	0.91	[m]
Height	1.8	[m]
Launch Mass	1000	[kg]
Engine Thrust	20	[kN]
Combustion Time	20	[s]

The subsystem arrangement of WIRES#013 is shown in Fig.4.

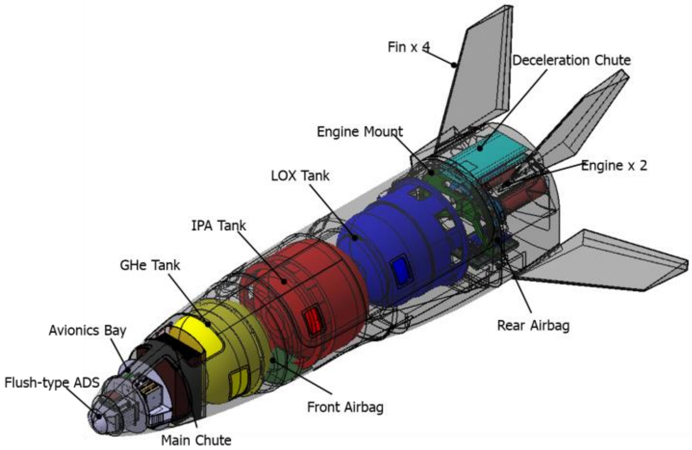

Figure 4: Subsystem arrangement of WIRES#013

WIRES#015 (Fig.5) has a thrust-variable LOX-Methane engine with 20 kN thrust designed by JAXA to reach the altitude more than 6km. It has the same length and weight of WIRES#013. The purpose of WIRES#015 is to validate the major critical technologies such as LOX-Methane propulsion system, RCS, CFRP-made vehicle structure, advanced nonlinear flight control system, real-time optimal flight guidance system, flush-type ADS system for the next suborbital flight of WIRES-X. The major specifications of WIRES#015 are shown in Table 2. Most of the subsystems are same for WIRES#013 and WIRES#015 as the former is the test bed for the later.

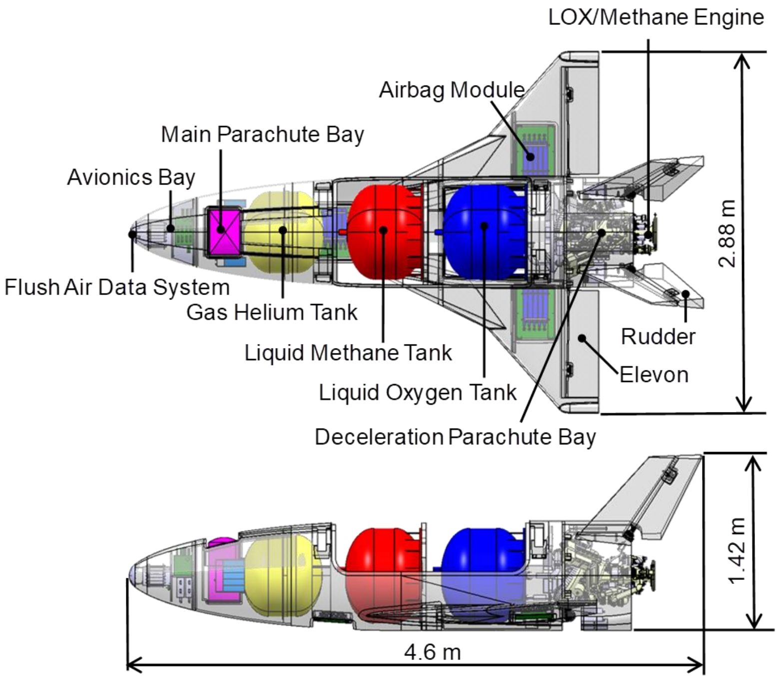

Figure 5: Two-view drawings of WIRES#013

Table 2: Major specifications of WIRES#015

Specifications	Value	Unit
Total Length	4.6	[m]
Body Length	4.0	[m]
Body Diameter	0.91	[m]
Height	1.42	[m]
Launch Mass	1000	[kg]
Engine Thrust	20 → 13	[kN]
Combustion Time	30	[s]

The nominal flight trajectory for the first flight test of WIRES#015 designed by flight simulation is shown in Fig.6. In this trajectory, thrust throttling profile is optimized for the maximum apogee altitude, and pitch angle is decreased during the coasting phase in order to realize attitude stability even without the effective operation of RCS. In the succeeding flight tests, the apogee altitude will be further increased by employing RCS. Since the bank angle in the gliding phase is still set to a constant value in this simulation, the guidance algorithm to improve the capability of the vehicle to fly to the target point will be implemented.

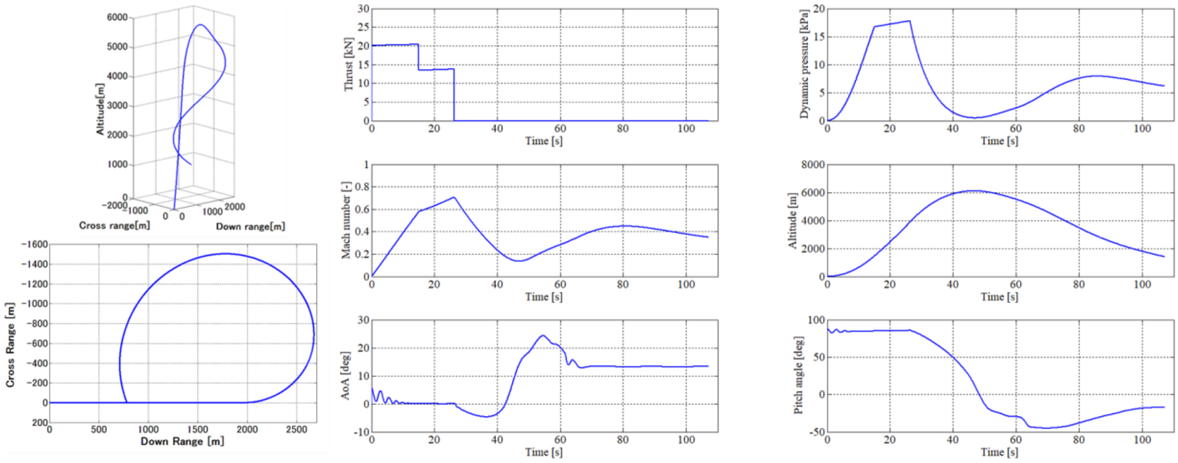

Figure 6: Nominal flight trajectory of WIRES#015

2.2 Structure

WIRES#015 and WIRES#013 have a fully composite semi-monocoque structure of CFRP skin with honeycomb sandwich. The nose cone is made of GFRP to prevent radio shielding. The structure consists of the fuselage, wing (no wing for WIRES#013), vertical fins, elevens and rudders. The fuselage is divided into the nose cone, front-body and rear-body (Fig.7). The engine will be mounted from the rear end of the vehicle to the thrust mount which is also made of CFRP skin with honeycomb sandwich. To insulate the heat from the engine, heat insulating blanket is also under research and will be applied to the rear body.

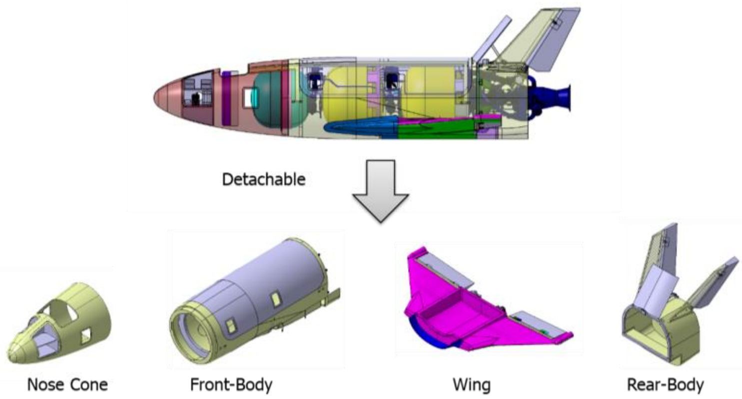

Figure 7: Vehicle structure of WIRES#015

2.3 Propulsion system

2.3.1 Main engine

WIRES#013 is propelled by two LOX-IPA engines developed by USC. The cut sectional view of the engine is shown in Fig.8. The system is a pressure regulated regenerative cooled propulsion system. Gaseous helium is utilized to feed the propellants to the combustion chamber. IPA will be used as the cooling agent for the engine. The cooling channels are milled along the outer surface of the combustion chamber. The two engines will provide the total thrust of 20 kN for 20 second combustion time. There is no gimbal or throttling mechanism for these engines.

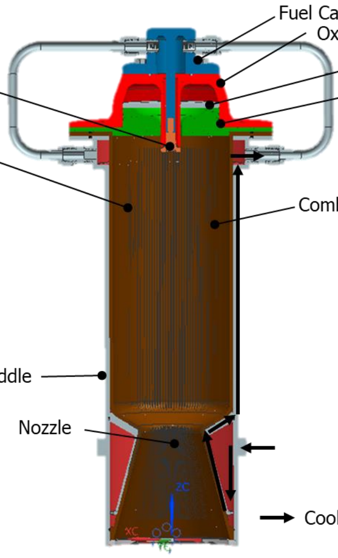

Figure 8: Cut sectional view of LOX-IPA engine of WIRES#013

The major specifications of the engine are shown in Table 2.

Table 2: Major specifications of LOX-IPA engine

Specifications	Value	Unit
Thrust	10	[kN]
Combustion Time	20	[s]
Isp (sea level)	242.6	[s]
OF Ratio	1.2	[-]

WIRES#015 is propelled by LOX-Methane engine (Fig.9) developed in collaboration with JAXA and IHI/IA. The system is a regenerative cooling fully expander cycle. The helium gas is utilised to start the turbo pump and to seal the pump purge line. It has a gimbal system for counteracting any thrust misalignment. It provides a thrust of 20 kN which is throttled down to 13 kN during the 30 second powered flight to mitigate the aerodynamic loading on the structure and to reduce the drag loss.

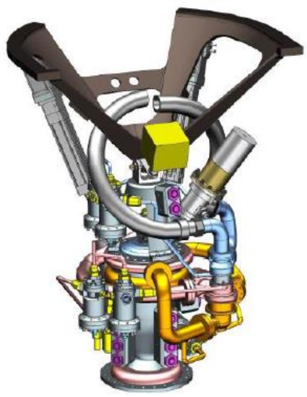

Figure 9: Image of LOX-Methane engine of WIRES#015

The major specifications of the engine are shown in Table 3.

Table 3: Major specifications of LOX-Methane engine

Specifications	Value	Unit
Thrust	20 → 13	[kN]
Combustion Time	30 or more	[s]
Isp (sea level)	255	[s]
OF Ratio	3.3	[-]
Maximum Gimbal Angle	± 5 (pitch and yaw)	[deg.]

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2.3.2 Tanks

The GHe tank is a CFRP-overwrapped aluminum linear tank. Liquid methane (for WIRES#013 it is IPA) and LOX tanks are made of aluminum (Fig.10). The tanks are mounted to the body structure using CFRP flange for GHe tank and using aluminum skirts for LOX/IPA/Methane tanks. Liquid propellant tanks will be equipped with a pressure diffuser to reduce the inlet speed of the gaseous helium, anti-vortex plate to regulate the turbulence of the outflowing propellant, baffles for reducing the sloshing effect, and level gauge to measure the level of the propellant. These tanks will be insulated with a 40mm thick heat insulating material (urethane foam).

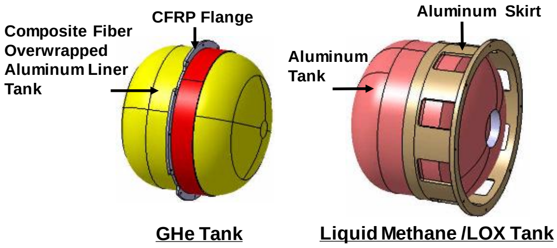


Figure 10: Schematics of tanks

2.3.3 Reaction control system

For a suborbital flight, there are not enough aerodynamic forces acting on the vehicle near the apogee. During this instance, reaction control thrusters (also called gas jet thrusters) are utilized for attitude control of the vehicle. This technology will be demonstrated using WIRES#015 whose apogee attitude is around 6km. In this case, air density at the apogee altitude is much larger than that of a suborbital flight. Therefore, a hybrid control law of the RCS and aerodynamic control surfaces is required to control the vehicle attitude effectively. Six gas jet thrusters are located on the end panel of the body as shown in Fig.11. The high pressure helium gas from the helium tank is utilised with a pressure regulator and solenoid valves which are used to switch on/off. This supply system is a blow-down type.

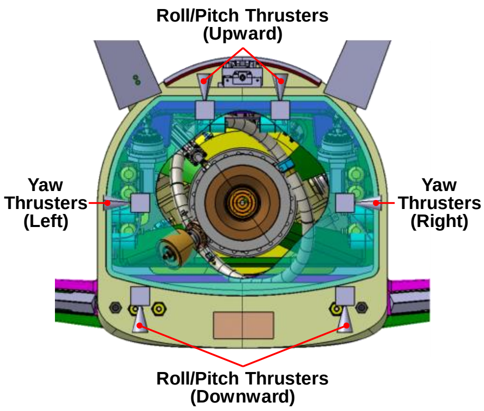


Figure 11: Location of reaction control thrusters

2.4 Avionics system

The avionics system (Fig.12) consists of guidance, air data, navigation, data storage, communication, engine and control computers which are connected by ARINC 429 bus system as commercial aircraft do. The only difference between WIRES#013 and #015 is that, WIRES#013 does not have guidance and navigation computers. Each computer has its own data loggers to reduce the load on the bus system.

In addition, there are dual emergency computers independent from the main avionics. When a system malfunction occurs during flight, and the control/engine computer of main avionics does not work, an emergency command is transmitted from the ground control center. The emergency computer on the vehicle shifts the command priority from main computers to the emergency computer using the relay, and emergency sequence is operated. The emergency system is a double fault tolerant system as the computers and the telemetry receivers are duplicated for redundancy. The EM model of the avionics system has been fabricated, and it is under testing.

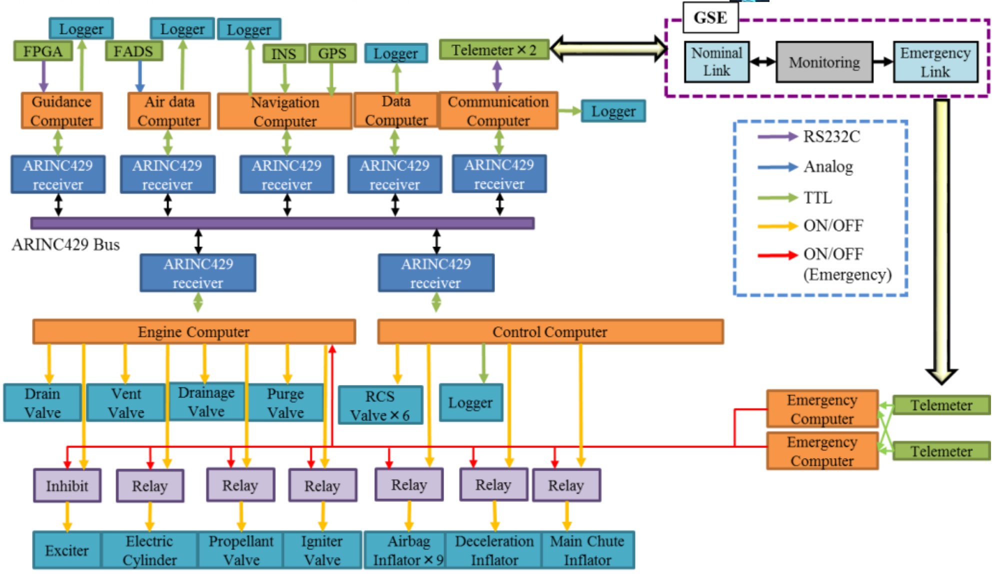


Figure 12: Block diagram of WIRES#015 avionics

2.5 Recovery system

WIRES#013 and WIRES#015 aim to touch down the ground without damage using two-stage parachute and three airbags (Fig.13). Deceleration chute and main chute which are ejected using cold gas inflators for automotive airbags. The target descending speed is 7-8m/s. Then, another inflators will be used for deploying and pressurizing three airbags.

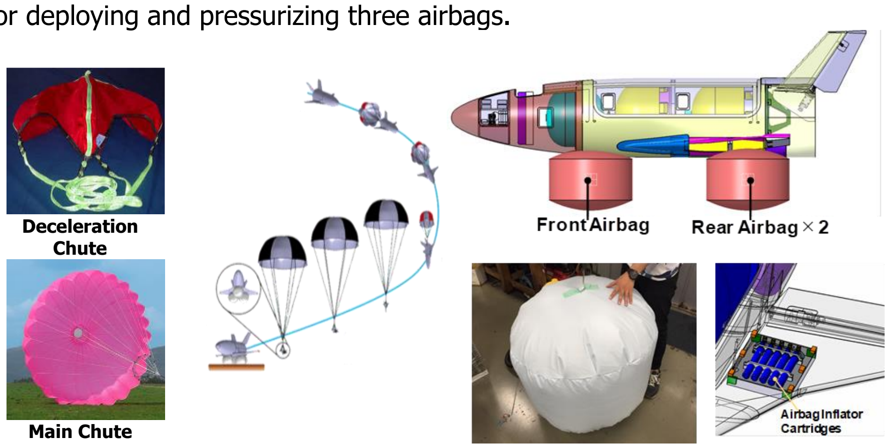


Figure 13: Two-stage parachute system and airbags

2.6 Launch site

The flight tests of WIRES#013 and WIRES#015 will be conducted at launch facility of FAR (Friends of Amateur Rocketry, Inc.), Mojave Desert in California of United States of America. Fig.14 shows the launch site and facilities (launcher, hangers and bunkers) of FAR.

Figure 14: Launch site and facilities of FAR

3 CONCEPTUAL DESIGN OF WIRES-X

WIRES-X is an unmanned suborbital vehicle that is currently in the conceptual design phase and is expected to be launched in 2020. The subsystems such as the complete composite structure, advanced avionics, RCS, recovery system and LOX-Methane propulsion validated in WIRES#015 will be utilized. The vehicle has a body length of 8.2m and weighs 4600kg. The main objective of this flight is to reach the outer space i.e. more than 100 km altitude. This vehicle will be propelled by three units of 20kN-thrust LOX-Methane engines.

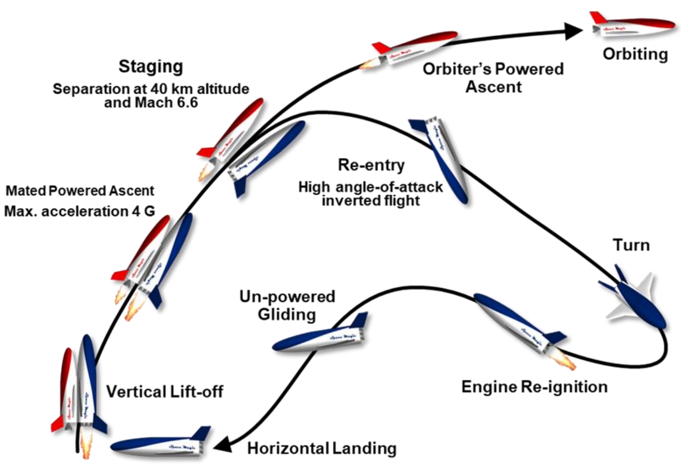
4 APPLICATIONS FOR FUTURE REUSABLE SPACE TRANSPORATION

In parallel to the aforementioned researches on critical technologies and their flight demonstrations, conceptual design studies of suborbital manned vehicle for space tourism and two-stage-to-orbit launch vehicle are being conducted by the authors. In order to handle the coupled design problem of the vehicle and trajectory associated with such vehicles, multidisciplinary design optimization techniques are employed to find design solutions with the minimum gross mass. The design study is extensively performed for a variety of technological options (tank type and rocket nozzle type) and missions (payload mass and target orbit) [8]. Some examples of the optimal design solutions obtained are presented in Fig.15 and Fig.16.

Vehicle specifications	
Gross mass [t]	23.6
No. of crews (pilot + passengers)	6
Apogee altitude [km]	120
Body length [m]	13.4
Dry mass [t]	7.9
Propellant mass [t]	15.7

Rocket engine specifications	
Number of units	9
Propellant	LOX/Methane
Vacuum thrust per unit [kN]	30
Vacuum Isp [s]	273
Sea-level Isp [s]	237
Nozzle expansion ratio	4.6
Propellant mixture ratio	3.3
Mass per unit [kg]	140

Figure 15: Artistic image and specifications of suborbital space tour vehicle



Vehicle specifications		
Total gross mass [t]		870.7
Payload mass (350km LEO) [t]		10.0
Booster	body length [m]	37.3
	dry mass [t]	64.6
	propellant mass [t]	597.0
	gross mass [t]	661.6
Orbiter	body length [m]	30.7
	dry mass [t]	34.6
	propellant mass [t]	174.5
	gross mass [t]	209.1

Booster rocket specifications	
Number of units	9
Propellant	LOX/Methane
Vacuum thrust per unit [kN]	1799
Vacuum Isp [s]	343
Throat area [m^2]	0.098
Nozzle expansion ratio	27.9
Propellant mixture ratio	3.5
Mass per unit [kg]	2680

Orbiter rocket specifications	
Number of units	2
Propellant	LOX/Methane
Vacuum thrust per unit [kN]	1081
Vacuum Isp [s]	370
Throat area [m^2]	0.054
Nozzle expansion ratio	137
Propellant mixture ratio	3.7
Mass per unit [kg]	1827

Figure 16: Flight sequence and specifications of TSTO launch vehicle

5 CONCLUSIONS

The authors have been preparing for the flight test of WIRES#014-3A which will be conducted in October, 2017. In parallel, the preliminary design of WIRES#013 and #015 was completed, and they have entered the detail design phases. The WIRES#013 will be fabricated and shipped to United States by early 2018, and the first flight test is planned in May, 2018. Subsequently, the flight test of WIRES#015 will be conducted in March, 2019 in order to validate major necessary technologies for the future reusable suborbital vehicle. These technologies will be applied to manned suborbital space tour vehicles and TSTO launch vehicles whose conceptual design studies are currently conducted by the authors as well.
This development project of winged rocket by the industry-government-academia collaboration is very rare even in the world, which is expected to contribute to the research progress of fully reusable space transportation system.

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REFERENCES

1. Yonemoto, K., Matsumoto, T., Choudhuri, A., R., Ishimoto, S., Mugitani, T., Makino, T., Kimoto, K., Ogawa, S., and Irino, Y.; 2014; "Development of Small Winged Rockets for Suborbital Technology Demonstration by Universities in Collaboration with Government and Industries"; 65th International Astronautical Congress; IAC-14-D2.6.10; Toronto; Canada; September 29 – October 3.
2. Yonemoto, K., Yamasaki, H., Ichige, M., Ura, Y., Gossamsetti, Guna S., Ohki, T., Shirakata, K., Choudhuri, Ahsan R., Ishimoto, S., Mugitani, T., Asakawa, H., Nanri, H.; 2016; "Winged Test Rocket with Fully Autonomous Guidance and Control for Realizing Reusable Suborbital Vehicle"; International Journal of Mechanical, Aerospace, Industrial, Mechatronic and Manufacturing Engineering; Vol.10, No.1; pp.96-107.
3. HIMES Research Group; 1987; "Conceptual Design of HIMES (Winged Test Rocket)"; Institute of Space and Astronautical Science; Ministry of Education; Japan (in Japanese).
4. Inatani, Y., Kawaguchi, J. and Yonemoto, K.; 1990; "Status of 'HIMES' Reentry Flight Test Project"; AIAA 2nd International Aerospace Planes Conference; AIAA 90-5230.
5. Gossamsetti, Guna S., Yonemoto, K., Yamasaki, H., Choudhuri, A., R., Ishimoto, S., Mugitani, T.; 2015; "Preliminary Design of Winged Rocket Test Vehicle with Liquid Methane Propulsion System"; 30th International Symposium on Space Technology and Science; 2015-o-1-03; Kobe, Japan; June 4 – 9.
6. Yonemoto, K., Fujikawa, T., Yamasaki, H., Ichige, M., Ura, Y., Gossamsetti, Guna S., Ohki, T., Shirakata, K., Irino, Y., Morito, T., Kato, Ishimoto, S., Mugitani, T., Erwin, D., Choudhuri, Ahsan R.; 2016; "Recent Flight Test Result of Experimental Winged Rocket and Its Future Plan for Suborbital Technology Demonstration"; 67th International Astronautical Congress; IAC-16-D2.6.1; Guadalajara; Mexico; September 26 - 30.s
7. Kamemoto, E., Yonemoto, K., Fujikawa, T., Yamasaki, H., Ichige, M., Ura, Y., Gossamsetti, Guna S., Ohki, T., Shirakata, K., Morito, T., Kato, T.; 2017; "Detailed Design of Winged Rocket WIRES#015 with Liquid Methane Engine"; 31st International Symposium on Space Technology and Science; 2017-o-3-12; Matsuyama, Japan; June 3 - 9.
8. Fujikawa, T. and Yonemoto, K.; 2017; "Conceptual Design Optimization of Several Types of Fully Reusable Winged Launch Vehicles"; 31st International Symposium on Space Technology and Science; 2017-o-3-14; Matsuyama, Japan; June 3 - 9.

