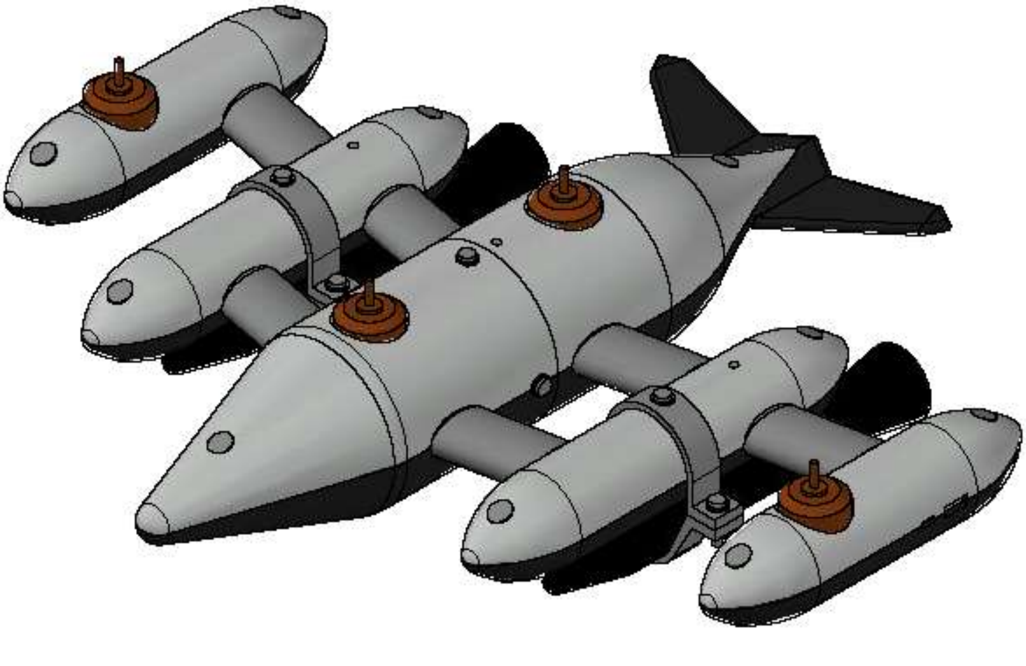
Giovanni Nicola D'Aloisio

Ikarus-X

Hybrid propulsion technology demonstrator



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by *Giovanni Nicola D'Aloisio*

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Vehicle Overview

Ikarus-X (henceforth referred to only as **Ikarus**) is a technological demonstrator for a faster, cheaper and safer space transport system than current solutions, based on electric and chemical propulsion and inspired by the *Space Shuttle*.

Flight Profile

Ikarus is a *vertical takeoff and landing vehicle*: at the beginning of each flight, once the on-board systems have been initialized, the motors of the electric propulsion system are started with a potentiometer, the propellers of which make it rise due to the principle of action and reaction. At this point it can be oriented using a joystick, in radio-assisted navigation.

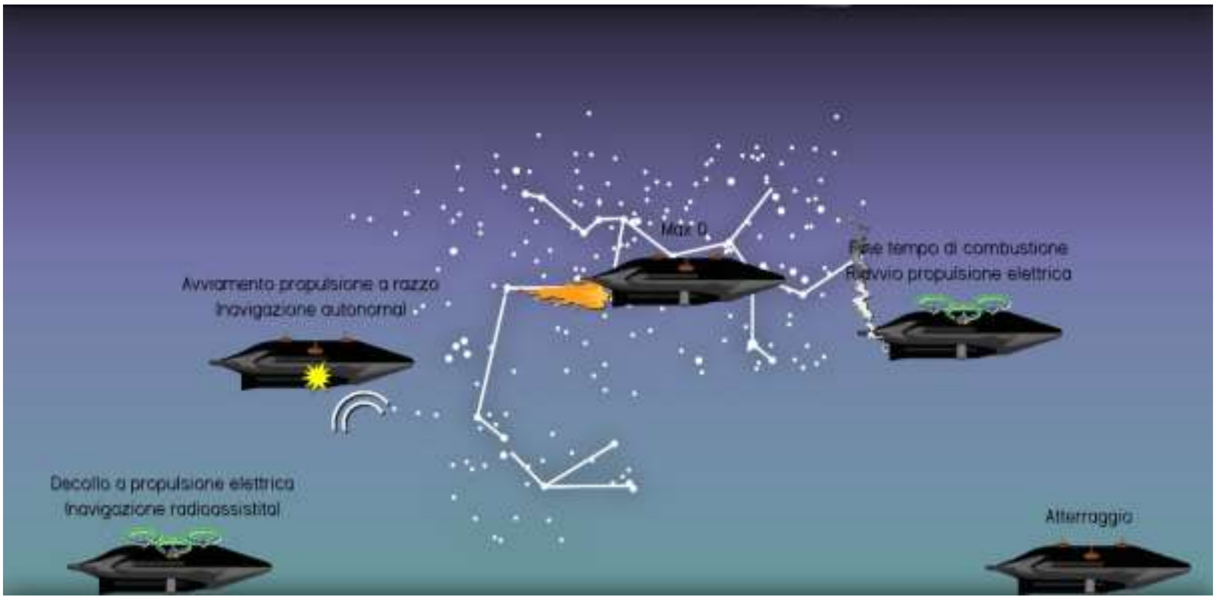

Fig. 1 – *The flight phases.*

During the test phase, the vehicle is manually placed at a maximum distance of 175 m from the ground transmitter and the button integrated in the joystick is activated, which switches the propulsion from electric to chemical. In this phase the frame is subject to the maximum stress, resulting from the large specific impulse produced by the two *Elektron* engines, fed by a highly explosive mixture of solid fuel. Once the fuel runs out, the electric propulsion system reactivates to perform a safe and fully automated landing.

The safety distance allows you to maintain the radio connection between the on-board board and the ground, and three LED lights of different colors (green, white and red) mounted in the upper part, if fixed, indicate the correct functioning of the on-board systems or, if intermittently, the functioning of the *Elektrons*. In the next sections these aspects will be better understood.

Framing

The frame is divided into five parts, numbered 0 to 2 on the starboard and port: S1 and S2 on the starboard side and P1 and P2 on the port side. The central segment is identified with the acronym S0.

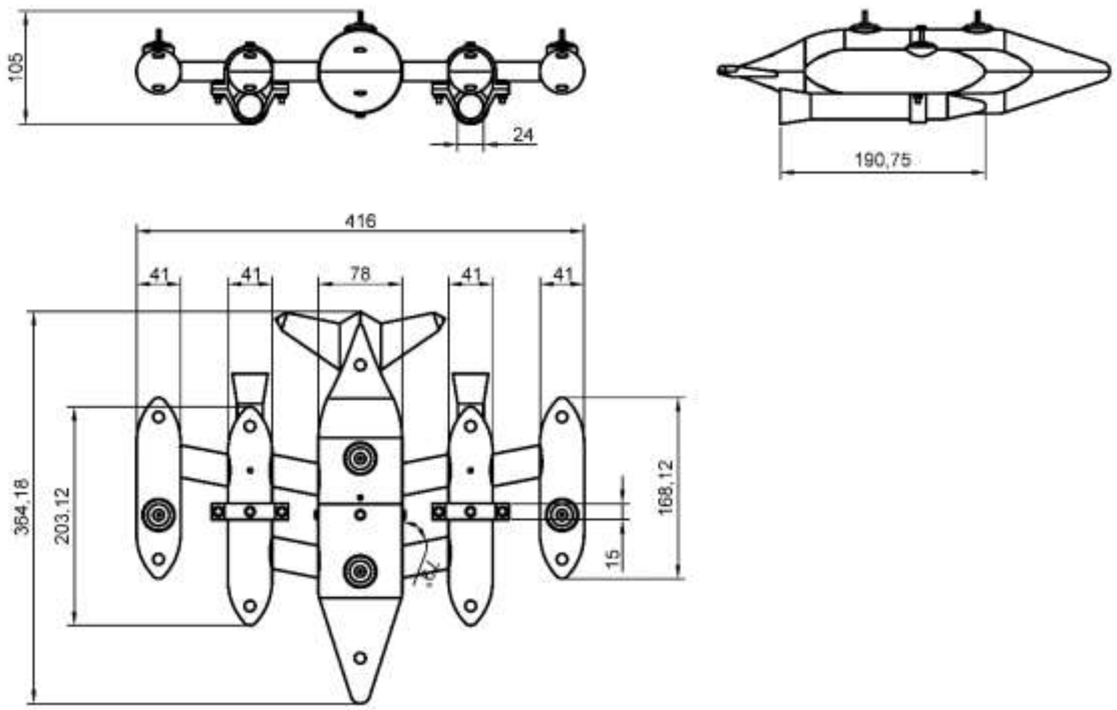

Fig. 2 – *The frame.*

The sectors are connected to each other with 6 interlocking arms, with the electrical system cables inside them. The support on the ground occurs without additional structures, and the S0 segment is equipped with a rear stabilizing fin, as well as being divided into two parts, which fit together and fasten together with four screws and bolts. Fully loaded, the vehicle weighs approximately 1.1 kg.

The following table shows the overall dimensions of the frame.

Sector/segment	Lenght [cm]	Width [cm]	Height [cm]
S0 = P0	36.4	15.8	9.8
S1 = P1	20.3	4.1	7.4
S2 = P2	16.8	4.1	4.1

The loading plan includes the motors of the electric propulsion system in compartments S2, S0 and P2, the chemical propulsion system below and the batteries inside compartments S1 and P1, equipped with holes that guarantee, with a dedicated fixing ring, good thrust maintenance, the *Electronic Speed Controllers*, the gyroscope and the receiver in the S0 compartment and the controller, the USB charging and maintenance sockets and the selectors in the S2 and P2 compartments.

The frame is made of *polylactic acid* (PLA) parts machined for *Fused Deposition Modeling*. Each segment is divided into two parts fixed to each other at the ends with the help of screws and bolts, the holes of which are filled with special covers in order to keep the C_D low and increase the solidity of the structure.

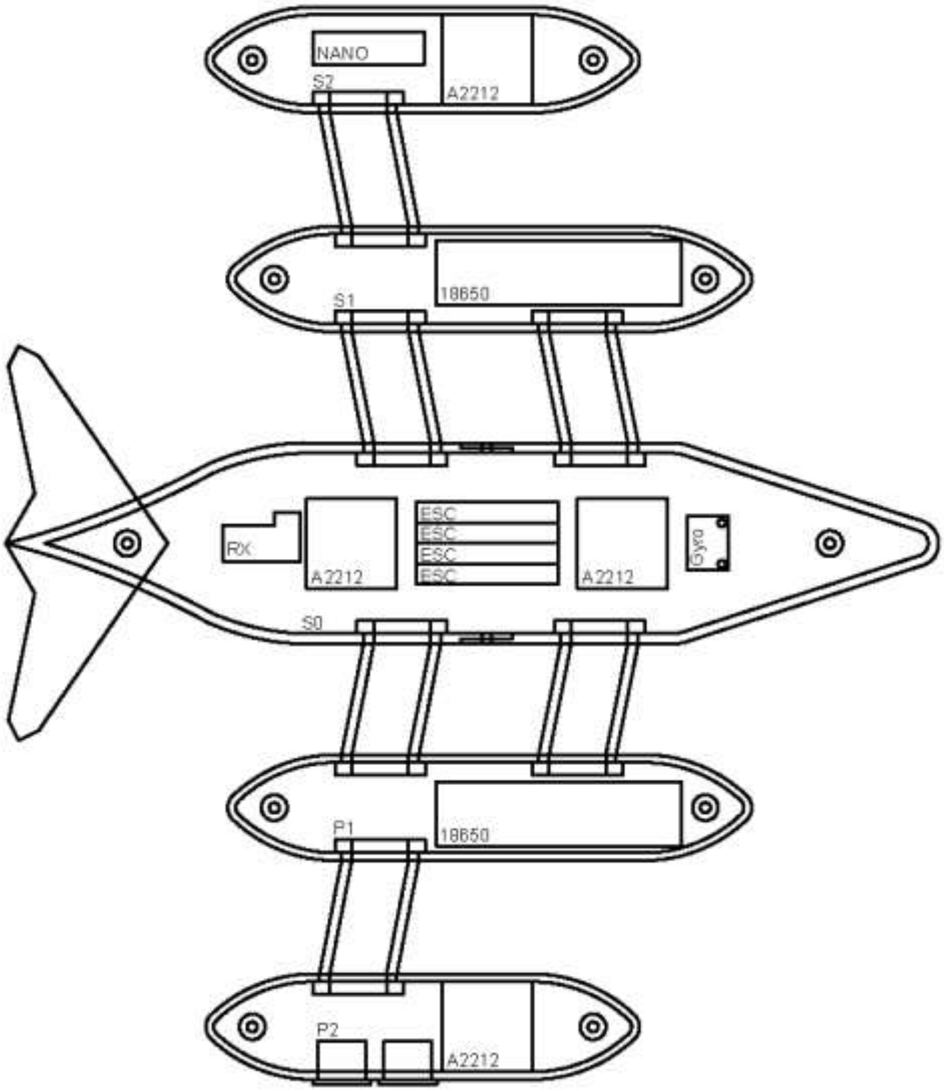

Fig. 3 – *The loading plan for a test flight.*

After having arranged the lower pieces of each segment on a plane, you need to fix the screws of the gyroscope, the receiver with its antenna, the controller, the switches and the USB sockets, the electronic speed controllers, the screws of the brushless motors, the signaling, the batteries and the electric cables in the appropriate seats; then, you can fix the upper covers of the segments S2, S0 and P2 using with screws and bolts, with the arms placed in the right holes.

The upper cover of the S1 and P1 segments can be fixed in a similar way only after having fixed it in turn to the upper part of each ring, with screws and bolts of the same type. At this point, to complete the assembly, simply insert the lower part of the ring into the *Elektron*, and join the two halves.

BLDC-powered Electric Propulsion System

The electric propulsion system is characterized by the presence of four electric motors controlled by the ATmega328P board through a speed controller. All utilities are powered by direct current with 18650 lithium-ion batteries (e.g., a COKE-PWSTICK-26-C should be enough for a short flight test).

In the brushless direct current motor, composed of a rotor (free to rotate and characterized by the presence of a permanent magnet) and a stator, a control unit supplies voltage to certain stator windings; when these are polarized, an electric current circulates in them which in turn produces a magnetic field. For this reason, the stator behaves like a second magnet. By alternating the power supply between the stator coils, a rotating magnetic field is obtained.

Fig. 4 – *BLDC engine in a floppy drive (courtesy of Wikipedia).*

Just as two magnets move until the opposite poles do not match, so the magnetic fields of the motor attract each other, but since the stator one is fixed, the rotor one produces mechanical power that can be exploited by a rubber wheel, a conveyor belt or, in this case case, a propeller.

The data of the motors and speed controllers used are shown below. Please remember that by their very design, the ESCs used prevent the instantaneous starting of the motors from any power supply, and the response to power changes is linear thanks to special RC filters.

The blades of a propeller are portions of a helicoid, the surface designed by a particle that rotates around an axis and simultaneously translates along the same axis. This motion, in this case imparted to the air, provides the vehicle with the upward thrust necessary for its lifting from the ground.

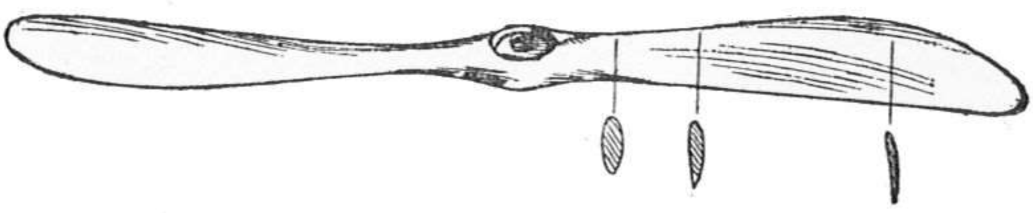

Fig. 5 – *Illustration of the propellers' profile.*

There are four propellers, arranged in a Greek cross, with two blades, with a diameter of 8 cm each. Furthermore, 2700 RPM/V motors allow high torque to be obtained with the same power supply that 1000 RPM/V motors would require.

Elektron Chemical Propulsion System

Ikarus can switch only once to the chemical propulsion system, based on the *Elektron*, a single-segment solid propellant rocket engine. The exchange occurs with a delay proportional to the response time of the ATmega328p microprocessor of the on-board controller.

The combustion chamber is a cylinder made of PLA, with an internal volume of approximately 46.1 cm^3.

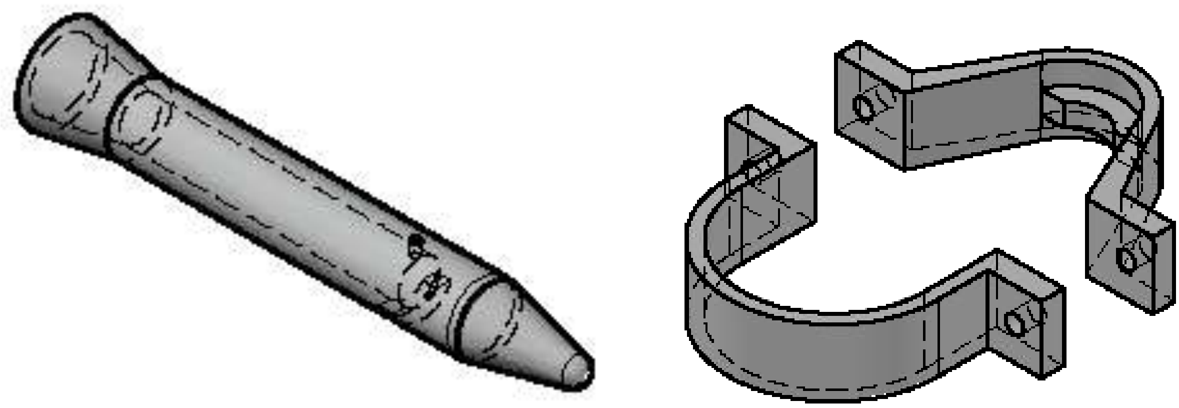

Fig. 6 – *Elektron v1 with the junction ring.*

White TNT is the name given to the bar of "homemade" explosive mixture, composed of 36% sucrose propellant and 64% potassium nitrate oxidizer which react according to the equations:

$$5\ C_{12}H_{22}O_{11} + 48\ KNO_3 \Rightarrow 36\ CO_2 + 55\ H_2O + 24\ K_2CO_3 + 24\ N_2$$

$$C_{12}H_{22}O_{11} + 24\ KNO_3 \Rightarrow 12\ CO_2 + 11\ H_2O + 24\ KNO_2$$

Sucrose (ρ = 1.59 g/cm^3; H_i = 17 MJ/kg) and potassium nitrate (ρ = 2.11 g/cm^3) were chosen for their simple supply, and each flight requires 26.4 g and 35.0 g, producing a total of 370 kJ of thermal energy. The preparation of the mixture occurs as follows.

After having finely pulverized the potassium nitrate, sugar is added to the mixture, and everything is slowly shaken by hand for approximately three minutes (the mixture is highly explosive and an electrostatic ignition can easily occur). At this point the mixture can be poured into the combustion chamber, already equipped with the ignition resistor, where it is pressed very slowly.

When Ikarus switches to autonomous navigation, the ignition process is automatic, timed and irreversible. When electric current passes, the resistance immersed at the bottom of the fuel rod produces a large thermal power in a few milliseconds, which completes the fire triangle, triggering the mixture to catch fire. A second version, named *Elektron v2*, will have staged combustion, in order to allow multiple firings in a single flight.

Navigation System

Ikarus normally operates in radio-assisted navigation, except in the testing phase. Two properly programmed ATmega328P (Arduino compatible) boards communicate with each other in the 433.92 MHz amplitude modulation band; of these, one is on the ground and the other on board.

The propellers are numbered clockwise from the forward one to the port one, by exponents; we will therefore have p^1, p^2, p^3 and p^4; those with an even index rotate counterclockwise, the odd ones clockwise, to compensate for the transversal thrust produced by the vortex motions of the surrounding air.

Radio-Assisted Navigation

The transmitter potentiometer is responsible for controlling the electrical power transferred from the batteries to the motors by means of the ESCs, and is unique for all motors.

The joystick, however, regulates the roll (around the x axis) and pitch (around the y axis) motions. With a tilt, the frame is subjected to a moment that makes it move in the direction in which it was "leaned". To induce rotation around an axis, it is sufficient to reduce or increase the power of one of the motors arranged along the direction perpendicular to that same axis.

For example, by rotating the joystick forward, the analogue input is encoded and amplitude modulated by the ground control board and transferred at a frequency of 433.92 MHz to the on-board antenna. The signal is decoded by the control board which sends it to the motor speed controllers (ESC); based on its value, a certain voltage and rotation frequency will be supplied to the corresponding motors.

Autonomous Navigation

The joystick is also equipped with a button with which, in sequence:

1. The electric propulsion system turns off;
2. A stopwatch starts;
3. The chemical propulsion system is triggered;
4. Once the engines have been turned on for a few seconds, the electric propulsion system is reactivated;
5. We return to radio-assisted navigation.

After landing it is possible to recharge the *Elektrons* and perform a new test.

If the trigger is missing or the thrust phase ends early, it is possible to reactivate the electric propulsion system with the same joystick button. Furthermore, with inclination greater than 30° the radio control is stopped and Ikarus reduces the power of the most suitable engines until the on-board gyroscope registers a transversally and longitudinally straight situation, and the radio control is reactivated.

Appendix A – Datasheets and Electronic Circuits

BLDC A2212 2700 KV ENGINES	
RPM/V	2700
Net mass	50 g
Mass	60 g
Size	27 × 27 × 26 mm
Shaft lenght	3.17 mm – 12.0 mm
Rated voltage	2 - 3 LiPo (< 8 V)
No-load current	1.8 A
Rated current	18.5 A
Maximum efficiency	80%
Optimal current	4 ÷ 10 A
Maximum power	240 W
ESC	20 ÷ 30 A
Peak current	14 ÷ 22 A

ELEKTRON v1	
Fuel/Oxidizer	$C_{12}H_{22}O_{11}/KNO_3$
Mixture ratio	25.3
Thrust (SL)	TBD
I_{sp} (SL)	TBD
Nozzle ratio	2.36
Lenght	17.9 cm
Mass	45 g ÷ 106 g

ELECTRONIC SPEED CONTROLLERS	
Mass	25 g
Size	45 × 24 × 11 mm
Rated voltage	5.6 V ÷ 16.8 V (2 ÷ 3 LiPo cells, 5 ÷ 12 Ni-MH/Ni-Cd cells)
BEC current	2 A
Rated current	30 A (with 40 A peaks in less than 10 seconds)

ELECTRONIC CONTROLLERS		
	UNO R3	**NANO**
Microcontroller	ATmega328P	
Rated voltage	5 V	
Optimal voltage	7 ÷ 12 V	
Digital – PWM Digital I/O Pins	14 - 6	22 – PWM
Analog Input Pins	6	8
DC Current per I/O – 3,3 V Pins	20 mA – 50 mA	40 mA – 50 mA
Rated current	19 mA	
Flash Memory	32 kB	32 kB
SRAM	2 KB	
EEPROM	1 KB	
Clock	16 MHz	
LED_BUILTIN	13	
Size	68.6 × 53.4 mm	18 x 45 mm
Mass	25 g	7 g

COMMUNICATION BOARDS		
	TX	RX
Model	MX-FS-03V	MX-05V
Range	20 ÷ 200 m	//
Rated voltage	3.5 ÷ 12 V	DC 5 V
Rated current	//	4 mA
Modulation	AM	//
Frequency	433.92 MHz	
Transmission speed	4 kBps	//
Transmission power	10 mW	//
Sensivity	//	-105 dB
Size	19 × 19 mm	30 × 14 mm
External antenna	Linear cable 25 cm with single or multiple nuclei	Single 32 cm-long solenoid

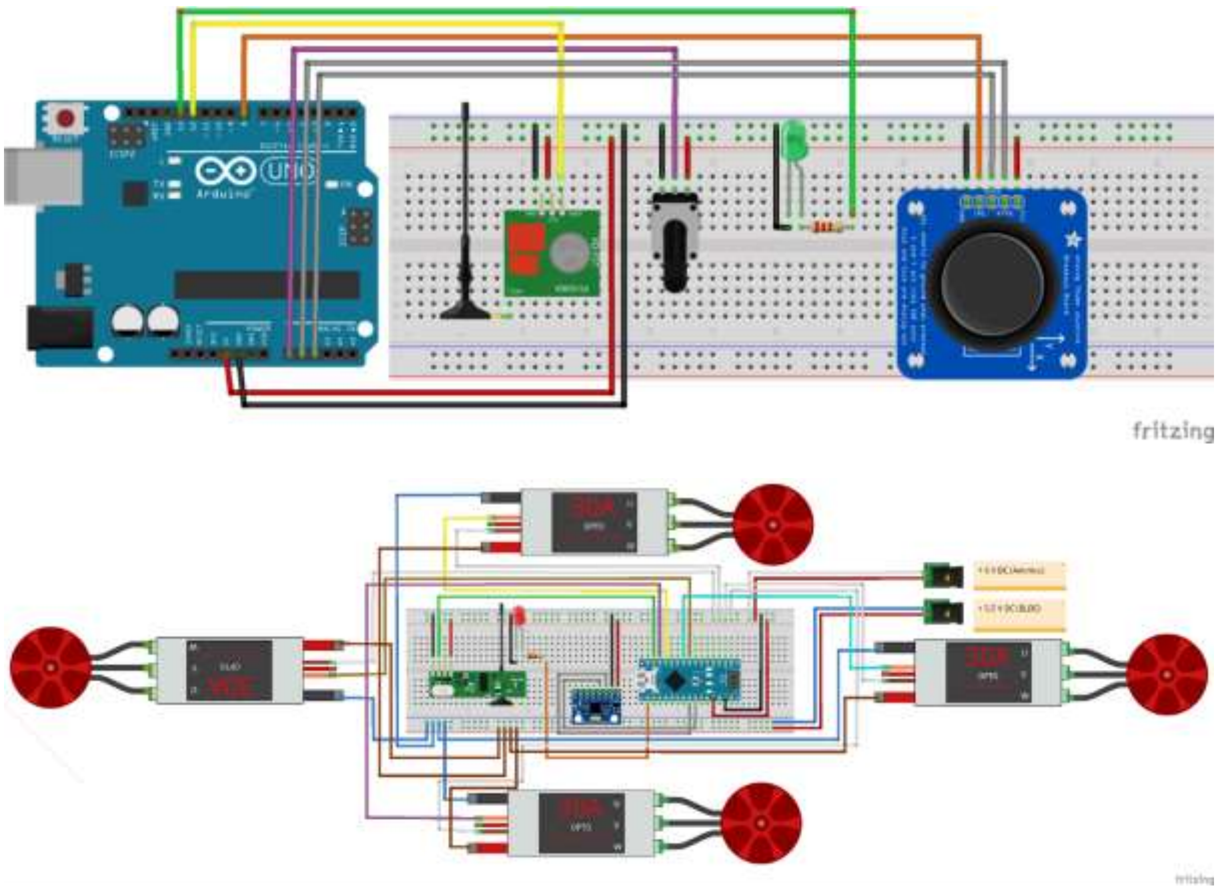

Fig. 7 – *Diagram of the control circuit on the ground (top) and on board (bottom).*

Appendix B – Future Developments

The Space Shuttle was initially conceived as a means of transporting cargo of scientific importance between the Earth and the Moon. Ikarus was designed to expand this idea, but compared to any other vehicle it sees the first phase of flight, that in the atmosphere of any celestial body, performed with electric and chemical propulsion; electric motors are the most powerful, reliable and efficient in the world.

Based on the same navigation system as Ikarus-X, Ikarus features two identical 3-in-1 thrusters. Starting from a basic linear scramjet structure combined with that of a propfan, air is pushed at more than Mach 1.2 towards the throat section, where combustion with methane, hydrogen or kerosene occurs; the outflow takes place in a linear aerospike, which allows maximum performance to be obtained at all altitudes. In the event that the atmosphere does not contain enough oxygen, the compression section is isolated to exploit the air stored on board. Once in space, each maneuver is performed with a Hall effect air ion thruster, placed on the crown of the scramjet and powered by the transparent aluminum-coated solar panels that cover the frame in the event of interplanetary flight, or by an onboard nuclear fusion reactor.

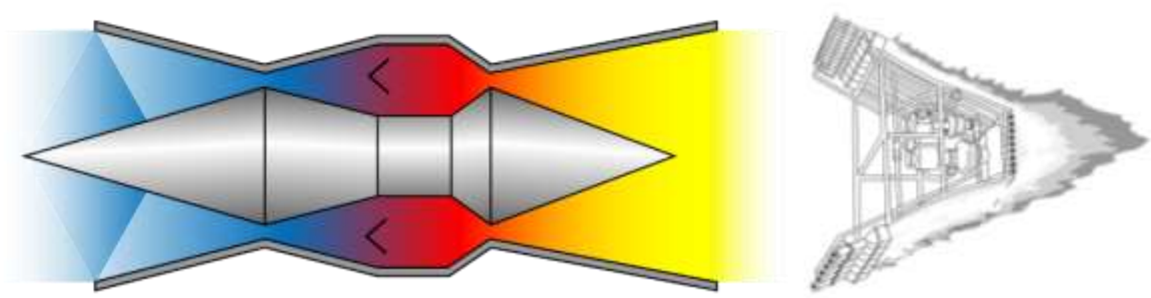

Fig. 8 – *On the left, schematic diagram of a ramjet (Wikipedia); right, aerospike engine (NASA).*

The S1, P1, S2 and P2 segments of Ikarus can contain modular cargo holds with a useful volume of 6 to 12 times that of a Space Shuttle; Furthermore, with the skills acquired during the development and use of the Spacelab and the Multi-Purpose Logistic Modules, cargo modules can be replaced to expand people transport capacity and support long duration flights as well as commercial transport contracts interplanetary, necessary for the growth of space tourism, the colonization of the Solar System, the exploration of new star systems, in particular that of Alpha Centauri, and technical and scientific progress.

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