Concept, Engineering, and Assembly of the Most Complex Space Analog: the International Space Station

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Abstract

Human space exploration is a challenging and dangerous activity requiring specialized training in space-like environments named space analogs. The International Space Station is the most complex available space analog and is the product of a collaboration between many international space Agencies (ISS). The assembly of the ISS modules has been carried out progressively over the years. Today, the ISS is the biggest orbiting human outpost and provides the scientific community with invaluable micro-gravity and space research opportunities.

Human space exploration poses a set of challenges summarized in the acronym RIDGE [1]: **radiation**, **isolation and confinement**, **distance from Earth**, **gravity fields**, and **hostile/closed environments**. Space Agencies set up their own astronaut training programs by simulating such harsh conditions in **space analogs**. Among all, the International Space Station (ISS) is the most complete space analog for human training and space research in micro gravity.

The ISS is, also, the most complex space-engineered system and the fruit of an international collaboration between five space Agencies: NASA, Roscosmos, ESA, CSA, and JAXA. Among the European countries, ASI, the Italian Space Agency, constitutes a particular exception due to its participation as both ESA's member state and partner in a bilateral agreement with NASA [2]. It is a permanent human outpost, as large as an American football field, traveling around the world at 400 km of altitude, with an orbital period of approximately 90 minutes, covering 85% of the Earth during its permanence in the LEO orbit [3].

The assembly of the ISS started with the docking of two modules launched in 1998, the Russian Zarya [4] and the US Unity [5]. During this year, mission STS-88 marked the first human intervention on the ISS, with numerous Extra Vehicular Activities

(EVA) planned to complete the interconnection of the modules [6]. The rest of the ISS has been built progressively, across the years, with the integration of additional pressurized modules. Table 1 provides a comprehensive view of such modules and their integration missions on the ISS sorted in chronological order. Furthermore, the ISS is provided with many unpressurized elements including robotic arms, External Stowage Platforms (ESP) holding spare parts, and the expandable Integrated Truss Structure (ITS) holding solar arrays, thermal controls, and other payloads [7, 8]. In its current state, the ISS is an integrated space system made of 16 pressurized modules, and many unpressurized elements, making it a 450 tons orbiting human outpost.

As an integrated complex space system of systems, the ISS can be characterized by the traditionally well-known spacecraft subsystems. However, such components are much more complex and include a whole set of new subsystems aimed at sustaining long-term human permanence in orbit.

The **Earth's Natural Life Support System (ECLSS)** [9] is the most basic requirement for human activity in space. It monitors gaseous element concentration in the air to keep it breathable while ensuring proper ventilation, pressurization, and humidity. It recycles approximately 50% of the oxygen and 98% of the water and filters CO2, microorganisms, and particulates. However, oxygen and water replenishments from the ground are still required from time to time. This subsystem also monitors fire, which is far more dangerous in space as it burns precious oxygen.

The **Crew Health Care System (CHeCS)** [10] is a suite of technologies with the purpose of monitoring astronauts' health and intervening to ensure safety in the ISS environments. On the monitoring side, as part of the CHeCS, the Environmental Health System (EHS) is delegated to ensure the atmosphere inside the ISS is not contaminated by microbes or potentially toxic substances derived from chemical processes. In the same frame, the Radiation System monitors the radiation, ensuring the dosage received by the crew does not exceed the guard levels, as the exposition in space is far higher than on Earth. On the other side, the Countermeasure System (CMS) provides all the technology and protocols necessary to reduce the severity of the impact of prolonged microgravity conditions on human muscles, bones, and physical structure in general. The Health Maintenance System (HMS) contains all the assets necessary to intervene in case of crew illness or injuries.

The **Electrical Power System (EPS)** [11] is a huge structure made of double-sided solar panel arrays whose orientation is aimed at maximum efficiency during the light time, and minimum drag otherwise. Different implementation choices between the US and Russia led to two different electrical managements, with Russia operating at 28 Volt in Direct Current (VDC) and the US at 124 VDC. The American system, for example, is capable of generating a power of almost 100 KW.

The **Thermal Control System (TCS)** is critical to keep the internal temperature of the ISS appropriate for both the crew and the onboard technology. The temperature is always kept at 24°C in the habitable modules. The passive TCS components [12] are insulation, surface coating, heaters, and heat pipes. The active TCS components [13] are made of connected liquid loops of water and anhydrous ammonia in a continuous heat exchange. The external Heat Rejection Subsystems (HRS) eventually radiate the heat away keeping the ISS temperature at the right level.

The **Integrated Truss Structure (ITS)** [14] is the base structure for the attachment of solar arrays, thermal control radiators, and payloads. It is made up of 11 segments and a Z1 component, mostly hosting moment gyroscopes and communication equipment.

The **Guidance, Navigation, and Control (GN&C)** [15] subsystem is responsible for the attitude control of the ISS. The ISS is provided with plenty of instruments dedicated to computing its orientation with respect to the Sun and the Earth as well as the position, including GNSS sensors, Rate Gyroscopes, and Star Trackers. Whenever possible, electric-powered systems like the Control Moment Gyroscopes (CMGs) are employed to orient the space station. However, when high-speed attitude adjustments are required, the thrusters employ the propellant to make corrections.

The **Propulsion subsystem** [16] ensures the ISS can avoid debris and assist other spacecraft in rendezvous and docking maneuvers by moving through the Service Module thrusters. However, it mainly keeps the along-track velocity stable to contrast the speed loss due to the atmospheric drag. The Service Module is also provided with 32 force attitude control systems, as previously mentioned. The system can also exploit a Progress docked at the Service Module for resupply as a primary boosting method.

Among the many situations in which high-speed orbital maneuvers may be required, space debris avoidance is one critical context. **The Micrometeoroid and Orbital Debris (MMOD) Protection** [17] is a subsystem made of Whipple and stuffed Whipple shields. These protections are meant to destroy the smaller debris while dispersing as much kinetic energy as possible. With the aim of improving human safety, habitable modules are located in the innermost part of the station, protected from unpredictable or unavoidable impacts along track. In this case, whenever the ISS is holed, EVA are conducted for repair.

The computers and data management subsystems [18] sum up to the order of millions of lines of code across the ground segment and the ISS for controlling and interfacing with the onboard technology. ISS computers, formerly using Windows, are now employing the Debian Linux operating system distribution [19].

The Communication & Tracking (C&T) [20] Subsystem provides the crew with the capability of communicating with the ground, internally, or with spacecraft and astronauts performing activities in the space surrounding the ISS. Through its RF links, the band is today upgraded to reach a 600 Mbit/s connection and enables real-time communication for any kind of task.

The space station was designed to stay operative for 15 years. Thanks to the successful realization and maintenance of the station, and the cooperation of all the partners, the mission duration has now been extended up to double its expected lifespan. The ISS will continue to produce inestimable scientific knowledge until its definitive dismission in 2030.

1 Appendix

Table 1 List of all the launch missions of the pressurized modules integrated in the ISS.

Module Name	**Launch Date**	**Purpose**
Zarya	1998	Russian-built, U.S.-funded; early power, propulsion, and storage.
Unity	1998	First U.S. module; connecting node between U.S. and Russian segments.
Zvezda	2000	Russian core; life support, command, and crew quarters.
Destiny	2001	U.S. lab; primary science research facility and host for the Oxygen Generating System.
Quest	2001	Joint airlock for U.S. EMU and Russian Orlan EVA suits.
Pirs	2001–2021	Former Russian airlock and docking port;
Harmony	2007	U.S. Node 2; connecting hub for international laboratories, provides crew quarters and utilities
Columbus	2008	ESA science lab module.
Kibō	2008–2009	Japanese Research Facility.
Poisk	2009	Russian docking port and secondary EVA airlock.
Tranquility	2010	U.S. Node 3; life support, hygiene, and exercise functions.
Cupola	2010	Observation deck with panoramic Earth-facing windows, supporting docking operations.
Rassvet	2010	Russian cargo storage and docking compartment.
Leonardo PMM	2011	U.S. Permanent Multipurpose Module; long-term storage
BEAM	2016	Experimental expandable habitable module.
IDA-2 and IDA 3	2016/2019	International Docking adapters.
Bishop Airlock	2020	Commercial airlock for deploying small satellites and payloads.
Nauka	2021	Russian multipurpose lab, crew quarters, and experiment platform.
Prichal	2021	Russian spherical module; multi-port docking hub.

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