(Preprint) AAS 24 – 076

EURISA: A EUROPEAN, COMPACT, SPACE-QUALIFIED IMU FOR SCIENTIFIC AND COMMERCIAL APPLICATIONS

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Following the H2020 European project Pioneers on the development of the new generation of a 6-axis (3 rotations and 3 translations) instrument for space seismology, EURISA aims at developing a compact, cost-efficient space IMU based on the same compact sensors. EURISA gathers four major space European industrials and laboratories: Airbus Defence and Space, ETH Zurich, DLR Bremen and Exail (formerly iXblue) that join their expertise and forces to develop, manufacture and validate an engineering model of the IMU by 2024. Qualification will follow-up, to offer a qualified design by the end of 2025. In this talk, Exail will present the technical and environmental specifications of the IMU. They have been carefully crafted to fit the needs of the main types of space missions: space shuttle; rover; entry, descent, and landing; interplanetary cruises. We will also present the architecture of the IMU to achieve those specifications and the development strategy. Finally, we share an up-to-date planning of the project and the latest technical results. EURISA development will contribute to European non-dependence and sovereignty in space for future missions and space exploration. It is supported by the European Union through the H2020 program under grant agreement n° 101004205.

INTRODUCTION

More and more spacecrafts launched and to be launched, from deep space exploration probes to CubeSats demonstrators or Mars landers, require Inertial Measurement Units (IMU) that enables to estimate trajectory and attitude. IMU are in general constituted of 3 gyroscopes, 3 accelerometers and various post-treatment algorithms.

Regarding sensors, the gyroscopes provide accurate and high frequency spacecraft attitude — in complement with other sensors — and angular rate information required to reduce or control the spacecraft attitude rate.

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The accelerometers are used to measure linear acceleration to bridge the information about the trajectory between position measurements by other sensors and for checking thrusters' efficiency, detect thruster failures or drive orbit control maneuvers.

In combination, accelerometers and gyroscopes are used for navigation of launchers and rovers or for landing, take-off, and orbital rendezvous. For all these missions, the IMU is an important equipment and very often a driver of the mission performance. A few high-end European IMU are available on the market like Astrix 1090A but with some critical non-European components —accelerometers for instance. However, no compact, ITAR-free and cost-effective IMU is available in Europe to date and both qualities are critical for future missions, especially compactness. This gap is currently filled by US products.

With the on-going development of solar bodies *in situ* exploration (Mars, the Moon, Titan, Phobos but also asteroids), there is a clear and growing need for a cost-efficient, yet reliable, space IMU. In this paper we describe such an IMU and a path for its development and qualification for space use.

TARGETED APPLICATIONS AND MISSIONS

Various types of mission should be considered to specify the relevant IMU for space. Based on future development, we describe in this section the missions that we identified as priority and their main consequences on the IMU design.

- "**Space shuttle**": The IMU is used during the launcher takeoff to control or monitor the navigation.
    - This kind of mission covers the IMU needs for putting small payload in orbit, Earth takeoff, such as CubeSat, LEO constellations.
    - For launcher missions, the IMU is submitted to severe mechanical environments during takeoff due to the engines.
    - In this severe case of operating environment, the critical parameters for this kind of mission are the followings:
        - High IMU range for both gyroscopes and accelerometers,
        - Gyroscope scale factor and misalignment requirements,
        - Accelerometer scale factor and misalignment requirements.
- "**Interplanetary cruise**": The IMU is used after launcher separation and is involved in vehicle navigation in order to reach a distant location.
    - This kind of mission covers the IMU needs for programs such as ExoMars (Carrier Module), MSR-ERO and Juice, missions at Lagrange point (SOLO) and in-orbit rendezvous (ATV).
    - The critical parameters for this kind of mission are the followings:
        - Gyroscope noise,
        - Gyroscope dead zone,
        - Accelerometer bias value and stability,
        - Accelerometer noise performance,
        - Accelerometer dead zone.
- "**Entry, descent and landing missions**" (EDL): The IMU is typically involved in the GNC task to ensure the safe landing of a vehicle.
    - This kind of mission covers the IMU needs for programs related to Mars Robotic Exploration, ExoMars (Descent Module) or Moon landing.
    - It is worth highlighting that for EDL missions, the IMU is submitted to harsh mechanical and thermal environment during atmospheric entry and powered descent.

    - In addition to the severe mechanical environment, the critical parameters for EDL missions are:
        - High IMU range for both gyroscopes and accelerometers,
        - Gyroscope scale factor and misalignment requirements,
        - Accelerometer scale factor and misalignment requirements.
- "**Rover**":
    - This type of mission is mainly driven by the needs of Mars Robotic Exploration programs and more recently the needs of Lunar programs or missions like MMX.
    - The key point for this kind of mission is to achieve the lowest mass and decrease the power consumption as much as possible. The required inertial performances are much less stringent in comparison with the other missions.

IMU SPECIFICATIONS

Following the work presented in the previous section and now that a subset of targeted applications was selected, Airbus Defence and Space derived critical sensor requirements for each application. Data is based on space IMU available on the market and Airbus Defence and Space know-how in space inertial navigation. Table 1 provides a comparison of the critical requirements for the different mission profiles.

Table 1. Critical IMU Requirements Depending on Mission Type.

	Interplanetary cruise	EDL and ascent vehicle	Rover
Gyro channel			
Range (full performance)	± 15 °/s	± 100 °/s ± 800°/s for aggressive EDL	± 10 °/s
Saturation range	> 500 °/s	> 800 °/s	> 500 °/s
Typical bias performance	0.15 °/h	0.15 °/h	0.5 °/h
Typical scale factor performances	300 ppm	50 ppm	1000 ppm
Accelerometer channel			
Range	± 0.1 **g**	± 12 **g**	± 1 **g**
Saturation range	± 0.5 **g**	± 20 **g**	± 3 **g**
Typical bias error	50 µ**g**	300 µg	500 µ**g**
Typical scale factor error	500 ppm	150 ppm	1000 ppm
Sampling rate	< 20 Hz	< 100 Hz	< 10 Hz
Mechanical environment (operating)	< 0.1 **g** (0 - 1 kHz)	11 $\mathbf{g}_{RMS}$ (0 - 10 kHz)	< 0.1 **g** (0 - 1 kHz)

Based on those mission-level needs, Exail and Airbus Defence and Space have defined a complete set of IMU technical and environmental specifications. Table 2 provides the main specifications that you could find in a datasheet.[1]

As of today, these specifications are the baseline for EURISA IMU development. No degradation of these specifications is foreseen, there might be some improvements (improved gyro measurement range for instance) depending on the first experimental results.

Table 2. Main IMU Specifications

Requirement	Value
Mechanical interfaces	
Mass	< 2 kg
Volume	130 × 130 × 120 mm
Environment / Operating conditions	
Temperature	Operating (full performance): − 10 to 50°C
Vibration	Operating (full performance): 13 $\mathbf{g}_{RMS}$
Shock	Operating: 1000 **g** half sinus 1 ms
Radiation	> 25 krad at component level (to be confirmed)
Lifetime	15 years in orbit
Performance – FOG	
ARW	< 0.0025 °/√h
Long term bias stability	0.5 °/h (max)
In-run drift	0.025 °/h (3σ)
Scale factor stability **(below: stability over 1 hour)**	300 ppm < 10 ppm
Orthogonality knowledge	< 175 µrad
Measurement range	± 800 °/s
Dead-zone	< 0.05 °/h
Performance – Accelerometer	
VRW	< 4 (mm/s)/√h
Long term bias stability	500 µg (max)
In-run drift	20 µg (3σ)
Scale factor knowledge	50 ppm (3σ)
Orthogonality knowledge	< 175 µrad
Measurement range	± 12 **g**
Dead-zone	< 1 µ**g** outside [− 10 m**g**, + 10 m**g**]
Electrical interfaces	
Power bus	22 to 50 V
Communication	UART RS-422
Power	12 W

IMU ARCHITECTURE

To achieve the specifications defined in previous section, the architecture is derived from Astrix NS, the latest space qualified three axis gyroscope from the Astrix family.[1] This development activity is similar to the one that allowed to derive the Astrix 1090A from Astrix 1090, by adding accelerometers and associated electronics.[2]

All in all, EURISA IMU is based on a space 3-axis gyroscope equipment developed by Exail and existing compact accelerometers to ensure a quick and cost-effective development. The architecture that is proposed in this document integrates both constraints, tends to limit as much as possible the design variation while fulfilling the specifications defined previously. This approach was chosen to fasten the development and optimize the cost of the final equipment.

Figure 1 presents the IMU overall architecture in a block diagram.

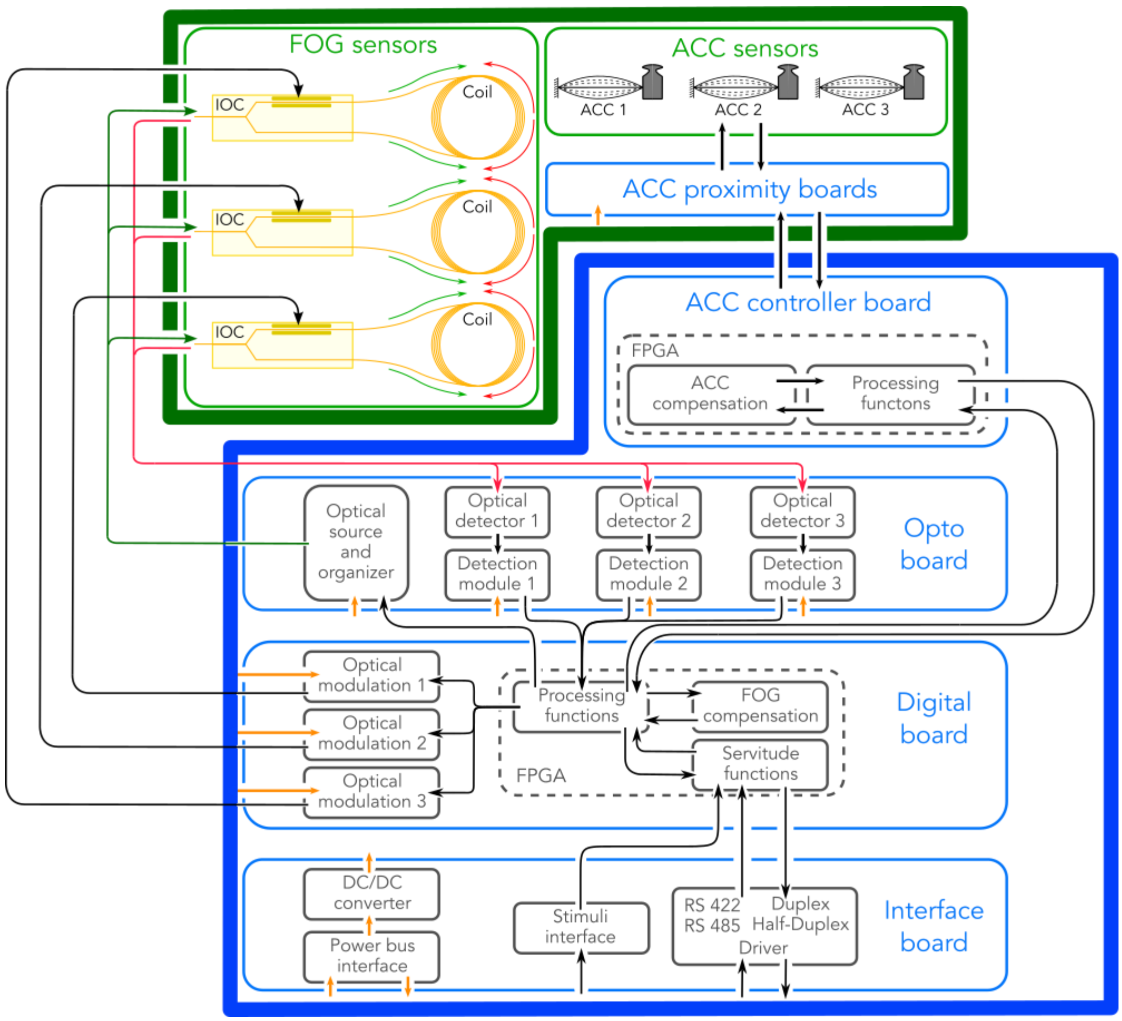

Figure 1. EURISA IMU Preliminary Architecture Represented as a Block Diagram. Each Blue (Electronic Boards) and Green (Sensors) blocks are Physical Parts. Large green and blue boxes respectively represent the damped pyramid and the electrical stack. Orange Arrows: Power Supply; Green/Red Arrows: in/out Light; Black Arrows: Signal Exchanges.

It is made up of following physical parts:

- **The inertial core** is composed of 3 gyrometers and 3 accelerometers organized on a single pyramid.
    - Dampers were designed and integrated under the sensor pyramid to accommodate vibration environments in both operational and non-operational conditions. There are no dampers in between the gyroscopes and accelerometers, which guarantee excellent movement integration during high energy event (efficient coning-sculling is possible during high vibration phase).
- One **accelerometer proximity board** (ACC-PE) per accelerometer (for a total of 3 boards in a complete IMU) located close to the accelerometer sensor. It is used for signal conditioning from and to the accelerometers.
- One **accelerometer controller board** (ACC-CE). It generates the "drive" signal necessary to drive the accelerometers, collects the signals from the accelerometers, converts them into an acceleration and transmits them using the data interface.
- One **opto board** dedicated to the fiber-optic gyrometers for optical detection and optical power management.
- The **organizer** stores passive optical components and the optical fibers.
- One **digital board** handles both the gyrometer and IMU algorithms including gyro compensation, lever arm compensation, coning-sculling, stimulation and anti-aliasing filtering.
    - The integration of those functionalities on board the IMU instead of the On-Board Computer (OBC) of the satellite as it is usually done with other IMU, will simplify satellite integration and operation for customers, especially smaller space companies.
- One **interface board** for power management and communication.
- The **mechanical packaging** to arrange all the IMU parts and for radiation shielding, see Figure 2. This packaging accommodates all the inertial sensors together with the dampers.

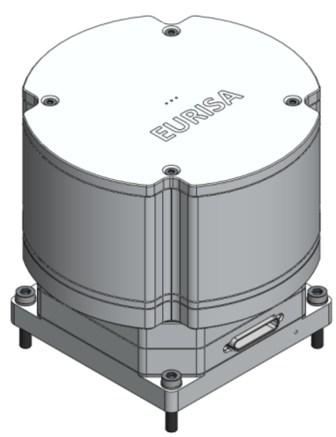

Figure 2. EURISA IMU External Mechanical Packaging.

HERITAGE AND FIRST RESULTS

As mentioned in introduction, EURISA IMU is based on different heritages:

- Astrix family regarding the fiber-optic gyroscope technology and space know-how.
- Astrix NS gyroscope for the compacity.
- Pioneers (H2020 European project) for accelerometers
- INS for launchers ensuring safeguard in flight in very harsh environments and using dampers.

Based on this set of heritages, the development is going fast. Indeed, as of today the following developments have already been achieved:

- Gyroscopes and accelerometers inherited from Pioneers and Astrix NS are ready.
- The interface board is finished and manufactured.
- The opto board is finished and manufactured.
- The digital board design is finished. Routed and tested individually.
- The dampers are designed and have been tested in shall and should mechanical environment.
- Two versions of the accelerometer proximity board were designed, and the final version has been validated.
- A first prototype version for testing of the accelerometer control board was prepared and received in summer 2023. It has been plugged into the accelerometers to estimate the performance. As a test design, this board includes several control inputs and will be redesigned more compactly for EM integration.

Based on all these sub-systems, we have already been able to make gyroscopic measurements. For instance, angle random walk (ARW) and scale factor measurements, see Figure 3 and Figure 4.

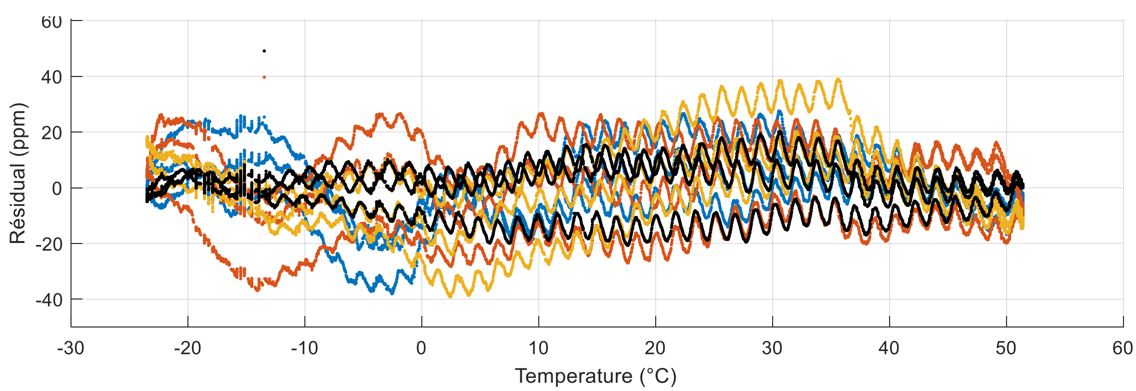

Figure 3. FOG Scale Factor Residue after Thermal Modeling.

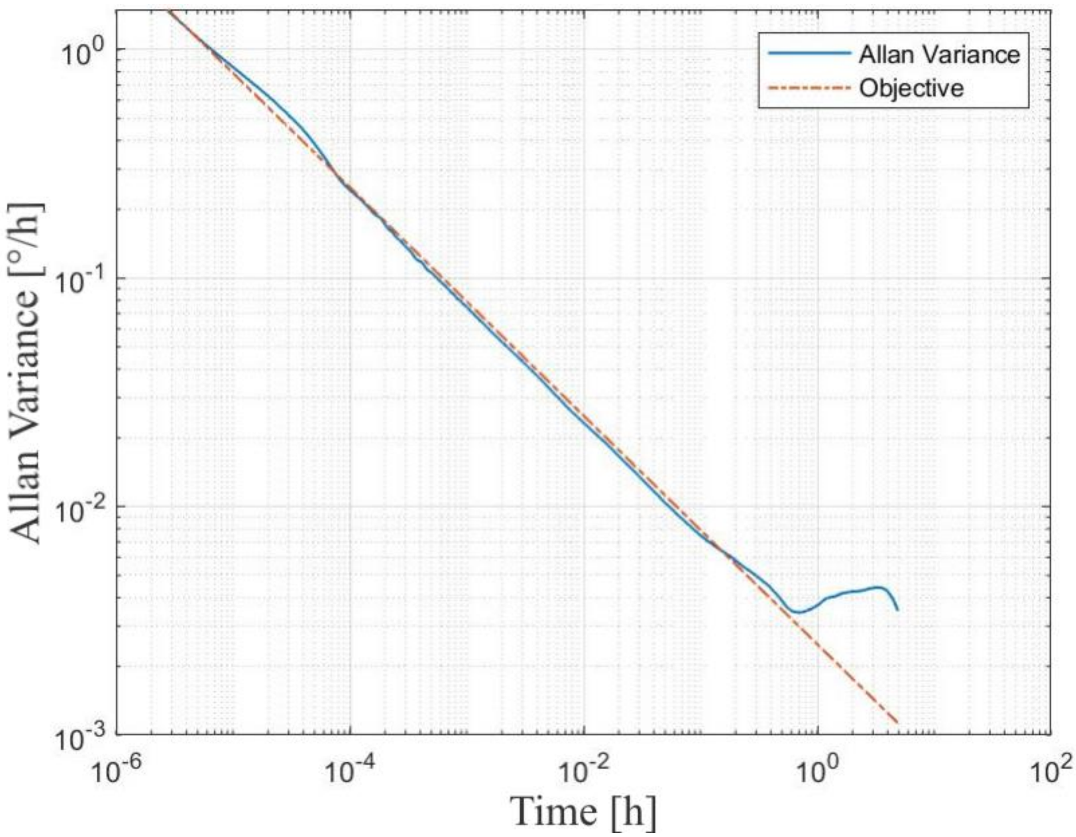

Figure 4. Angular Random Walk. The Increase at Long Duration is Due to Environmental Variation as the Measurement Chain is not Modeled in Temperature for this Test. It is not Imputable to the Performances of the Sensors. ARW = 0.00231 °/√h

The damper design has also been finished and they are being manufactured, see Figure 5. The main parameter for the damper's definition, their attenuation, is presented on Figure 6.

Figure 5. Photograph of the Sensor Pyramid Mounted on its Set of Dampers for the Test Campaign in Vibrations.

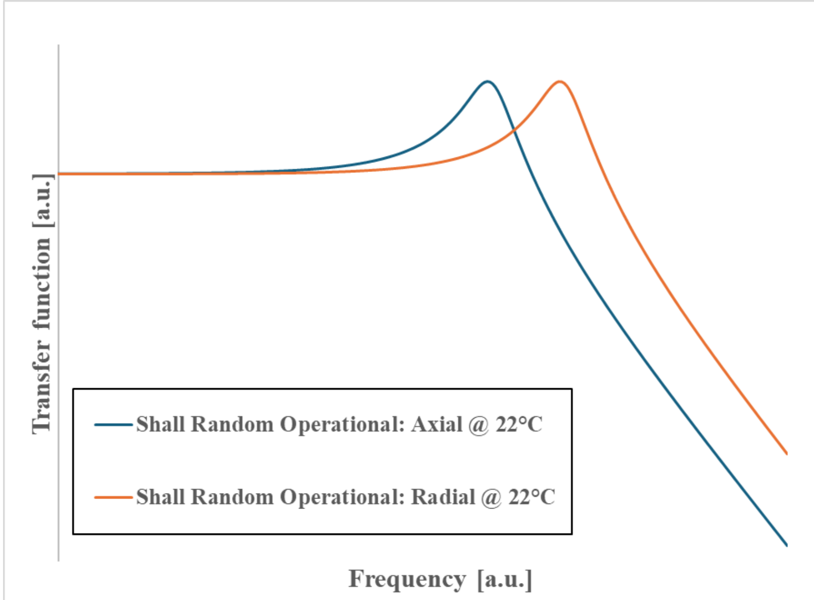

Figure 6. Theoretical Mechanical Transfer Function of the Dampers in Axial and Radial Vibrations. Scales and Units are Deliberately not Displayed.

The mechanical response of the damper set has been tested on a shaker at shall and should levels of sine and random vibrations, see Figure 7. It also endured shocks. For this test campaign, the dampers carried 3 non-compliant FOG and accelerometers arranged in a pyramid shape. The experiment validates that the behavior of the damper set fit the theoretical prediction with no mechanical damage, active components (set of accelerometers) remained functional.

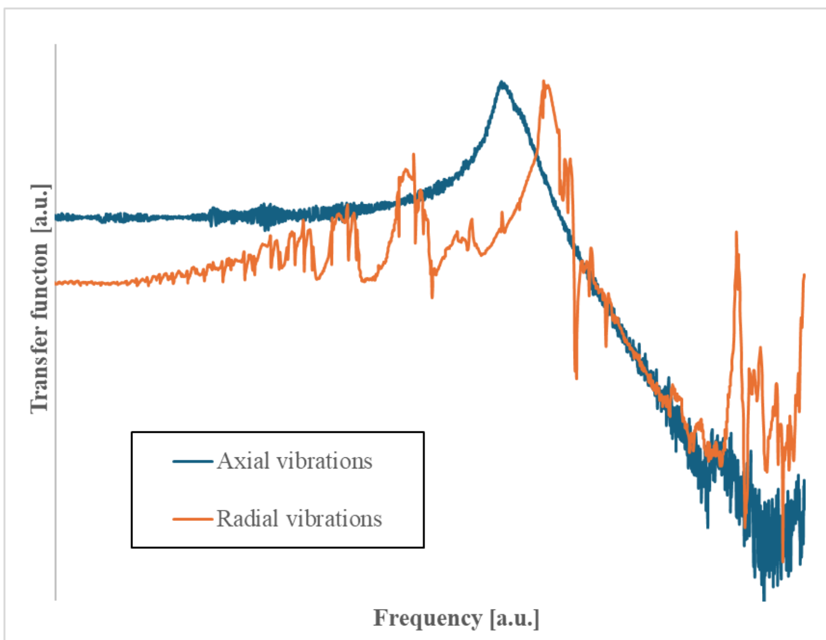

Figure 7. Mechanical Transfer Functions of the Damper Set Measured during Sinusoidal Vibrations at 0.5g. The Damper Set was Mounted with the Sensor Pyramid for the Test. Scales and Units are Deliberately not Displayed.

The different subsystems have been assembled into a flat IMU in December and January, see a schematic on Figure 8. For this the connections between the subsystems have been checked and validated. VHDL code has been written for the sensor raw data processing. The human machine interface has been adapted for the IMU. The IMU test plan is written. Once the raw sensor data extraction is validated, the first IMU tests in environment are lead. It concerns functional tests in vacuum and performance tests such as temperature cycling for temperature model construction.

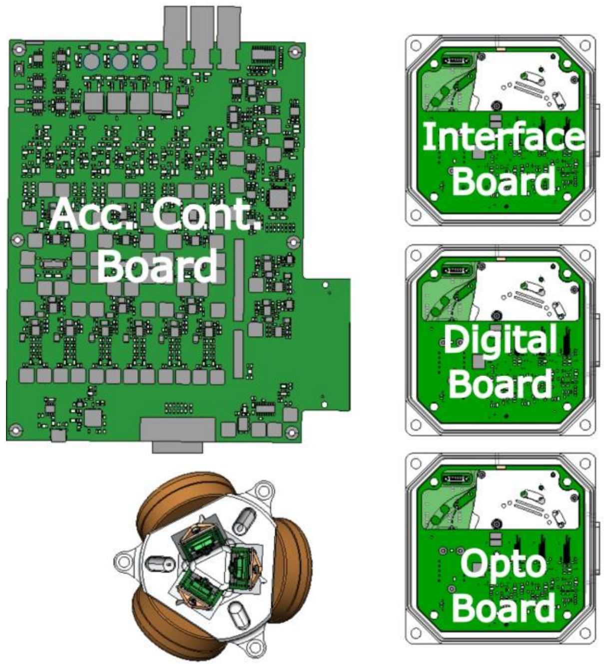

Figure 8. Schematic of the Flat IMU Including the 3 FOG and 3 Accelerometers Mounted on a Pyramid (bottom left), the Accelerometer Controler Board (Acc. Cont. Board), the Interface Board, the Digital Board and the Opto Board. The Different Components are Connected by Optical and Electrical Wires.

Building the connection between subsystems in the flat IMU and verifying the IMU functions allows refining the function specification on the accelerometer controller board. These conclusions will be taken into account for the next iteration design on the accelerometer controller board. The shape of this new design prepared by ETHZ will fit in the IMU housing.

Following, the VHDL code for navigation algorithms will be implemented on the FPGA chip on digital board.

DEVELOPMENT PLANNING

The EURISA project was kicked off in January 2021 for a duration of three and half years until June 2024. During the first two years of the project the consortium mainly worked on the following subjects:

- IMU and subsystems specifications and architecture.
- Mechanical design adaptation and development (including dampers).
- Gyroscope sensor and electronic boards design adaptation and development.
- Accelerometers sensor and electronic boards design adaptation and development.
- IMU process.
- Tests on the first electronic subsystems.

Until the end of the project, the consortium will integrate the different subsystems that were developed, first into a flat IMU (Q3 2023) and then into an engineering model (Q3 2024), fit, form and function of the future flight models.

The engineering model will be fully tested, to de-risk the design both at Exail and DLR Bremen facilities, testing will include functional, performance, mechanical environments, thermal vacuum environments, dynamic tests on rate tables.

Following EURISA project, the partners are currently looking for means of following the development until QR at the end of 2025.

Engineering models will be commercially available from Q2 2025.

EURISA PARTNERS WORKING ON THE IMU DEVELOPMENT

EURISA IMU development relies on the participation and commitment of four European players already well established in the field: Airbus Defence and Space, ETH Zurich, DLR Bremen and Exail. They have had the chance to work together in different contexts and they have complementary knowledge in all needed scientific and technological aspects to succeed in this development:

- Space electronics at Airbus Defence and Space, ETH Zurich and Exail.
- Inertial sensors at Exail and Airbus Defence and Space.
- System integration at DLR Bremen.
- Algorithms for navigation, sensor hybridization at DLR Bremen and Exail.
- Environmental characterization and space products experience at all partners. Except for radiation for which the tests will be subcontracted to one of the few European companies having that kind of facilities.

REFERENCES

[1] Astrix NS Datasheet: https://www.ixblue.com/photonics-space/inertial-navigation-for-space/

[2] Astrix 1090 – 1090A Datasheet: https://www.ixblue.com/photonics-space/inertial-navigation-for-space/