Fusionics Components Development

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COSYLAB | UK Atomic Energy Authority

What is Fusionics?

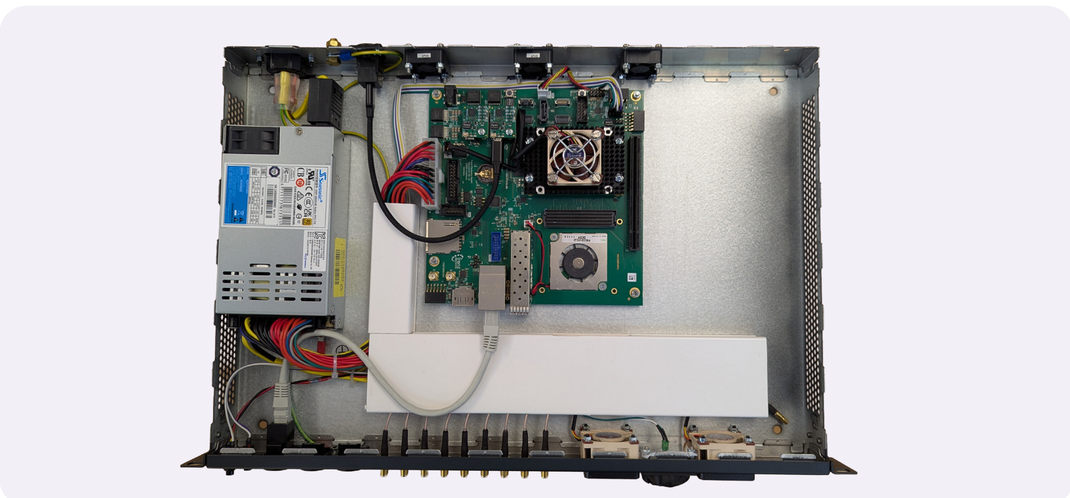
- Fusionics integrates fusion technology and advanced control systems, much like avionics revolutionized aerospace engineering.
- It addresses the unique challenges of controlling fusion reactors, including complex dynamics and multi-scale processes.
- Fusionics enable high-speed, deterministic control for mission-critical fusion power operations.
- It supports modular, reusable, and scalable platforms for fusion reactor management.
- Fusionics unites advanced hardware, software, and AI to optimize plasma stability and performance.
- It fosters interoperability and lifecycle management through standardized processes.
- Fusionics bridges the gap between research, industrial applications, and economic scalability.
- Aiming to create a global supply chain, Fusionics supports the industrialization of fusion technology.
- It prepares the workforce of the future by driving innovation in control systems and fostering cross-disciplinary collaboration.

ISFNT RESEARCH

Nimbus: Diagnosing in Real Time

Nimbus is a diagnostic platform for Fusionics, primarily used for neutron radiation measurement in a mixed neutron–gamma field. The specifications require processing raw sensor data in timescales of tens of nanoseconds, which demands high-performance FPGA-based real-time acquisition.

Cosylab has developed **real-time interfaces** using an FPGA for UKAEA across several board projects. For example, on the MAST-U board (Virtex-7), we utilised a core to pack RTDI frames and transmit them over UDP/IP via 1 GbE Ethernet. We later ported the Ethernet core to the NIMBUS board (Xilinx Ultrascale+), with which **we evaluated a 10 GbE Ethernet link for a feasibility study,** subsequently implementing it and significantly increasing throughput capacity.

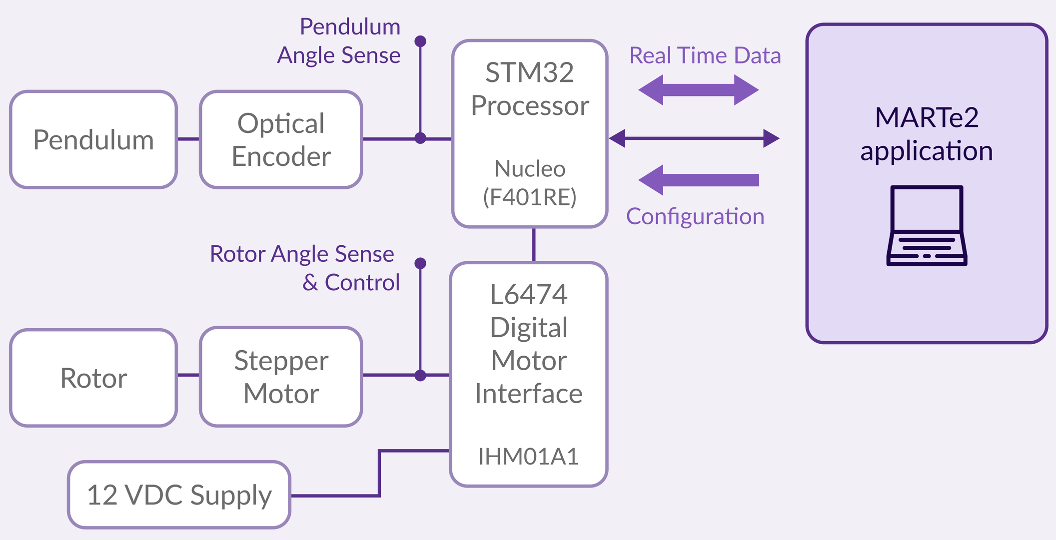


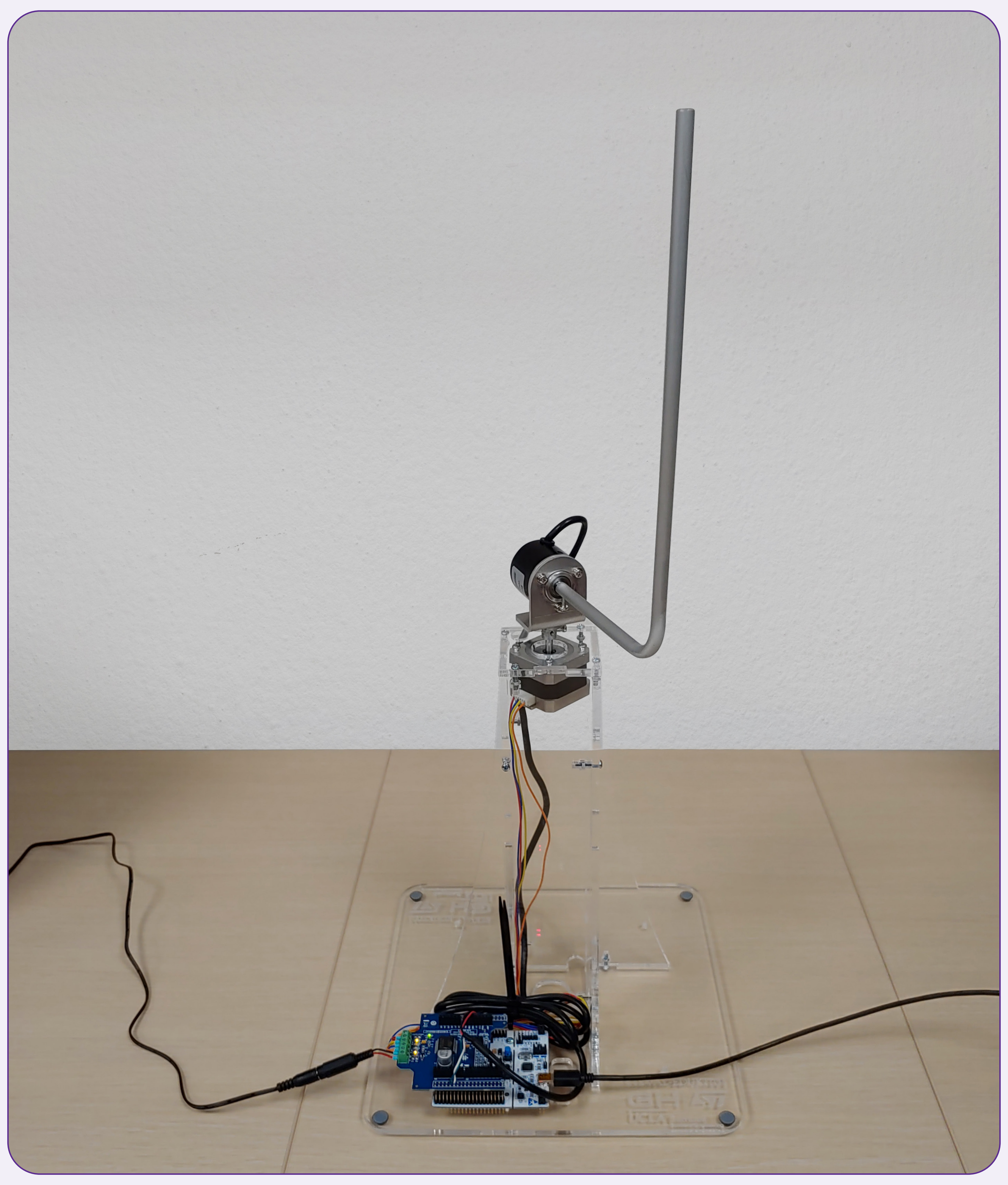
In addition to the Ethernet transport, we also established the **Aurora 64b/66b protocol** on both the IRIS and NIMBUS boards, providing **a low-latency solution for transmitting high-speed ADC data between boards.** We validated the implementation with hardware-in-the-loop (HIL) testing, using an FPGA-based ADC emulator to generate data, transmit it via Aurora, and then verify data integrity and continuity upon reception.

By integrating these advanced communication protocols into the FPGA fabric, NIMBUS is evolving into **an industry-ready diagnostic and data acquisition platform,** capable of addressing not only fusion challenges but also quite varied high-speed instrumentation problems across domains.

Real-Time Control Showcase: Inverted Pendulum

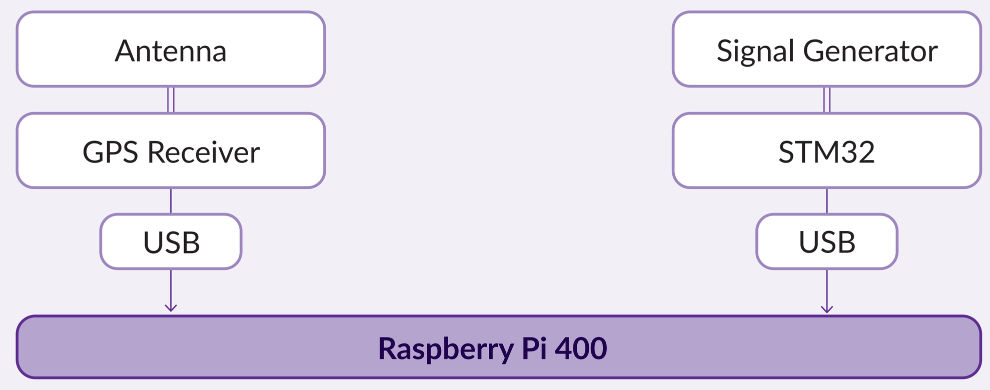
The Inverted Pendulum Prototype showcases **Real-Time Control with MARTe2.** It demonstrates the real-time regulation of an inverted pendulum, which parallels the dynamic challenges encountered in plasma control for fusion devices. The inherently unstable pendulum requires precise and continuous feedback to maintain equilibrium—mirroring the control demands in plasma stabilization. Implemented using the MARTe2 real-time framework, the project highlights its capabilities in managing complex, high-speed control tasks. This **showcase exemplifies how MARTe2** can be leveraged for advanced control systems, reinforcing its relevance and potential for applications in fusion research.





Synchronized Data Acquisition with Low-Cost Equipment

This project showcases **precise, timestamped data acquisition using cost-effective hardware,** demonstrating MARTe2's adaptability to resource-constrained setups. A GPS receiver, connected to a Raspberry Pi, provides accurate time synchronization, while a function generator, interfaced via an STM development board with an ADC, produces and samples analogue data. By integrating these components under the MARTe2 real-time framework, we achieve precise, timestamped signal processing on low-cost platforms. This approach opens pathways for affordable, high-precision data acquisition systems with potential applications in fusion and beyond, highlighting MARTe2's versatility across diverse fields.



Validating a Real-Time Data Network with MAST-U

The RTDN project aims to **develop and validate a high-performance real-time data transport system** for **MAST Upgrade.** The goal is to achieve deterministic, low-latency communication (the requirement for the RTDN latency was 10us) using **standard technologies,** such as Ethernet, IP, and UDP, as well as **commercially available components** such as NICs and switches.

We have created a dedicated testbed to aid in characterising end-to-end performance, focusing particularly on latency determinism and jitter. We have also implemented extensive host-side optimisations, including operating system tuning, CPU core affinity, memory bandwidth allocation and kernel-bypass networking with DPDK. In addition to packet I/O, we used DPDK for lock-free inter-process communication via huge pages and zero-copy data transfer.

While the current platform relies on off-the-shelf hardware, the production system will integrate custom FPGA-based UDP sources to meet the strict real-time requirements of scientific data acquisition.

By combining commodity networking with purpose-built hardware, the RTDN project advances both the understanding and the practical implementation of real-time networks in large-scale physics experiments.