AN AUTOMATED PRODUCTION TEST SUITE FOR CAPACITIVE ALIGNMENT SENSOR CONDITIONING ELECTRONICS*

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Abstract

The High Luminosity upgrade of the Large Hadron Collider (HL-LHC) at CERN requires exceptional alignment accuracy of accelerator components to reach the luminosity targets and to ensure reliable beam operation. This accuracy is achieved with the help of the Full Remote Alignment System (FRAS), which employs a capacitive Wire Positioning System (WPS) to monitor the position of magnets, RF cavities, and other accelerator components relative to a stretched, conductive, reference wire. Each WPS sensor measures distance offsets with respect to this reference wire with sub-micron-level resolution. The sensors are connected via dedicated cables to specially designed WPS conditioning electronics for signal processing and data acquisition. These modules operate as application specific cards within CERN's Distributed Input/Output Tier (DI/OT), a standardized framework designed for modular electronics operating in radiation-exposed environments.

To support the large-scale production and verification of over 400 WPS conditioning modules, an automated Production Test Suite (PTS) has been developed. The PTS streamlines firmware programming, automates test execution and ensures full traceability through integration with CERN's Enterprise Asset Management (EAM) platform and the Engineering Data Management Service (EDMS). This paper presents the design and validation of the PTS for WPS conditioner electronics, focusing on hardware–software integration and its role to enable reliable production testing for the HL-LHC.

INTRODUCTION

The HL-LHC aims to increase the collider integrated luminosity by roughly one order of magnitude over its operational period, tightening tolerances on the alignment of magnets, crab cavities and other interaction-region components to the sub-100 µm level over several hundred metres [1, 2].

The FRAS achieves this with sensors to monitor and remotely correct these positions from the CERN Control Centre [3]. One of these types of sensor is the WPS sensor which, mounted on to the machine elements, measures the differential capacitance between a ground-referenced conductive wire and four electrodes inside an aluminium housing [4].

The associated WPS Conditioner is a radiation-tolerant DI/OT [5] application card that excites the sensor, performs charge-balancing readout and provides digitised position data to a DI/OT Systemboard [6]. With over 400 of these units to be manufactured and tested, a scalable and reproducible validation process is required, given the complexity of the WPS system.

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WPS SYSTEM AND VALIDATION CHALLENGES

WPS Sensor and Conditioner

The WPS system combines capacitive sensors and dedicated conditioner electronics to measure transverse displacements of a reference wire with sub-micron-level precision. The WPS sensor (see Fig. 1a) consists of a split aluminium body with a circular bore and four printed electrodes on flexible PCBs inside the bore [7]. A grounded Carbon–Kevlar wire of 0.8 mm diameter passes through all sensors along each side of the interaction-region.

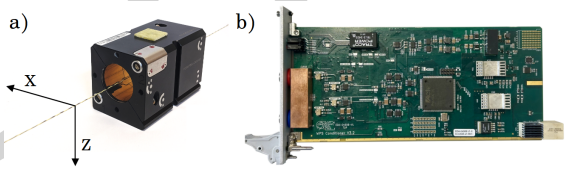

Figure 1: a) WPS sensor with Carbon-Kevlar wire passing through it. b) WPS Conditioner board.

Opposing electrode pairs form two differential channels measuring vertical (Z) and horizontal (X) displacement of the wire relative to the sensor centre. The WPS Conditioner (see Fig. 1b) excites the electrodes with a sinusoidal reference in the 1 kHz to 10 kHz range, drives an active shield on the sensor and cables and uses feedback-controlled charge balancing to obtain a value proportional to the displacement.

Limitations of Manual Validation

Validating the performance of this system currently relies on a dedicated bench (see Fig. 2) using a physical WPS sensor mounted in a mechanical jig with a real wire that can be positioned at five test points by rotating two knobs.

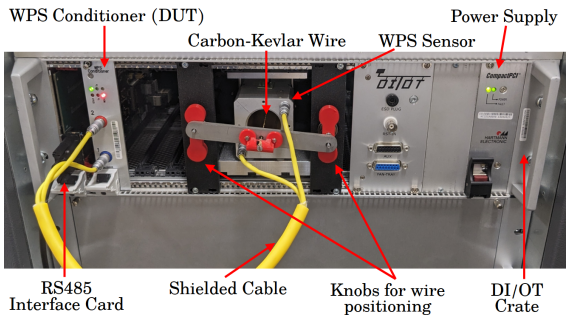

Figure 2: Manual WPS validation bench (to be replaced).

The card under test is installed in a DI/OT crate, connected to the sensor via cables, and read out over an RS-485 interface using dedicated software. Operators adjust potentiometers on the card while watching live readouts, compare the measured positions with reference data and manually fill paper test reports. This approach is slow with repeated mechanical interventions, does not directly exercise all digital interfaces and is prone to mistakes in entering results. With hundreds of cards to qualify and set up, a more scalable and repeatable validation approach is required.

PTS REQUIREMENTS

To address these limitations, the following functional requirements were defined for the PTS [8]:

- Program the FPGA via JTAG.
- Exercise and validate all external interfaces: Low Voltage Differential Signalling (LVDS) Serial Peripheral Interface (SPI), RS-485, Inter-Integrated Circuit (I^2C) and hardware reset.
- Realize a hardware-equivalent WPS sensor in four discrete positions, using discrete mechanical capacitors, achieving differential capacitance within 5 % of that of a real sensor.
- Verify position accuracy within ±150 steps at the centre and ±1000 steps at the extremities, and stability within 5 steps over at least 30 s.
- Measure the active shield waveform amplitude, frequency and total harmonic distortion (THD) up to 10 kHz without overloading the driver.
- Support batch testing of up to eight cards.
- Integrate with CERN's documentation infrastructure so that every test execution is linked to a unique asset and its report is uploaded and versioned automatically.

HARDWARE ARCHITECTURE

In line with these requirements, the PTS hardware was designed as a modular system that integrates with the existing DI/OT crate (see Fig. 3). It consists of a main board that occupies the DI/OT System board slot [6], eight sensor emulators that connect to each of the front-panel sensor inputs of the eight Conditioners (under test) and two 4-channel USB oscilloscopes for active shield measurement.

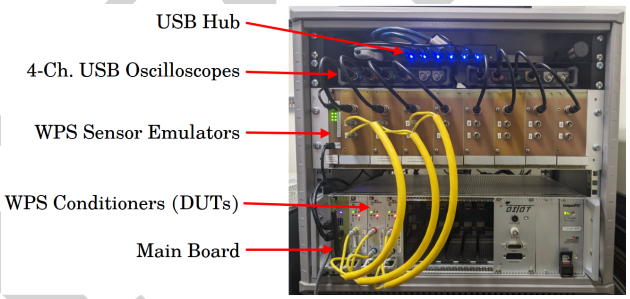

Figure 3: PTS hardware overview.

Main Board

The main board is installed in the DI/OT system slot, which routes backplane connections to up to eight application cards (e.g., WPS conditioners).

A Raspberry Pi Compute Module 5 (CM5) [9] (see Fig. 4) serves as the embedded controller, chosen for its rich peripheral set (SPI, I^2C, UART, USB, HDMI, Ethernet, Wi-Fi) and mature software ecosystem.

An LVDS transceiver stage converts the CM5 3.3 V SPI signals to eight independent LVDS SPI links, with per-slot chip-selects. All MISO lines are multiplexed to avoid a single faulty card pulling down the bus.

RS-485 communication is implemented with a MAX3490 transceiver connected to the CM5 and also accessible via a front-panel USB-B connector.

The backplane I^2C bus and reset lines are brought to CM5 GPIOs and expanders, and a buffered reset line allows the PTS to assert the Conditioner reset per slot.

For FPGA programming, direct GPIO connections from the CM5 connect to the backplane and Microchip's DirectC JTAG programming library [10] is used to send the bitstream.

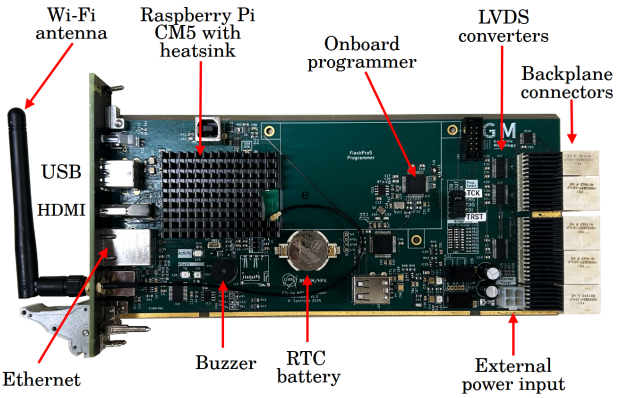

Figure 4: PTS main board featuring a Raspberry Pi CM5.

Sensor Emulator

The sensor emulator provides a programmable capacitive load that mimics one WPS sensor at four specified wire positions exercising -6, 0 and 6 mm offsets from the centre in horizontal and vertical directions.

The required differential capacitance values were determined from measurements of a real WPS sensor installed on its calibration bench [7]. The measured differential capacitance is around 142 fF for the full scale positions [8] and was used as the design target.

The emulator realises these values with carefully adjusted mechanical capacitors and signal relays to switch between the different positions. Command selection of the four positions is controlled from a simple microcontroller, connected via USB RS232 to the main board.

Active Shield Measurement

The active shield driver on the Conditioner produces a ±10 V sinusoid with configurable frequency, driving the sensor cable shields and front-end copper shields [8]. In a pre-series production of the Conditioner cards, a defective DC–DC converter reduced the ±15 V supply rails, leading to clipped waveforms of only about 7 V_{pp} even though the frequency remained correct. To measure these signals, two 4-Channel USB oscilloscopes are integrated in the rack and controlled from the main board via USB [8].

The active-shield signal of each Conditioner is routed to a dedicated oscilloscope channel through the sensor emulator, allowing automated measurement of fundamental amplitude, frequency and THD up to the fifth harmonic without additional analogue design.

SOFTWARE AND INTEGRATION

Test Sequencing and GUI

The PTS control software is built around the pypts framework already used at CERN for other DI/OT production test benches [11]. Test sequences are defined in YAML files that specify the order of actions, parameters (e.g. SPI register addresses, RS-485 frame codes, emulator positions) and expected pass/fail limits for each step.

A graphical user interface (GUI) provides operator prompts for actions such as inserting cards or scanning serial numbers, displays live progress and logs detailed results per step. At the end of each run, pypts generates a CSV file with raw results and an HTML summary that highlights failed steps and key measurements [8].

FPGA Programming Workflow

On start-up, the operator selects the Conditioner hardware revision and scans the card serial numbers. The CM5 then invokes Microchip DirectC [10] to program the corresponding FPGA bitstream over JTAG for all installed slots, verifying each device before proceeding to functional tests [8].

The same PTS firmware images are used as in the final installation firmware chain, ensuring consistency between production validation and operational deployment.

After programming the FPGA, the previously scanned serial number is stored onto the EEPROM for future automated identification.

Traceability with EDMS and EAM

CERN's Enterprise Asset Management (EAM) system is used for tracking physical assets. In addition CERN's Engineering Document Management System (EDMS) is used to store a variety of documents, which can be attached to assets. The PTS links each execution to a specific asset by querying EAM to check that the scanned serial number exists and is in a suitable state for testing.

Upon completion, the PTS either creates or updates an EDMS "Report" document referenced from the asset entry [8]. In addition, selected details from the test run (e.g. FGPA firmware version, test date, etc.) are pushed into dedicated EAM custom fields to allow quick filtering and statistics on large batches.

VALIDATION

Hardware Validation

The LVDS SPI implementation was validated using a mixed-domain oscilloscope by reading registers at various clock frequencies [8]. Reliable communication was demonstrated up to about 10 MHz, limited by signal rise/fall times of roughly 30 ns, and a conservative operating point of 1 MHz was selected for production use. In addition, JTAG programming was verified by comparing the behaviour of a previously validated, known-good Conditioner before and after reprogramming.

Functional Coverage and Fault Detection

Using the sensor emulator, the PTS can automatically sweep all four positions per channel, check that the measured step values fall within the specified tolerances and monitor stability over configurable time windows [8].

Tests on pre-series cards showed that stability requirements (within 5 steps, equivalent to around 2 µm, over 30 s) can be verified even when emulating long cable capacitances.

The integrated oscilloscopes reliably distinguish between nominal 20 V_{pp} active-shield waveforms and degraded signals caused by faulty DC–DC converters [8].

Requirements Coverage

The implemented PTS hardware and test sequences satisfy the functional requirements defined in the previous sections, including interface coverage, position accuracy, position stability checks, active-shield characterisation and integration with CERN's documentation infrastructure.

The only remaining open point is the full demonstration of batch testing with eight cards in a single crate, which is under commissioning; the current setup has so far been operated with single cards while using the same hardware and software framework.

CONCLUSION

An automated PTS for the WPS Conditioner has been designed, implemented and validated, targeting the large-scale production required for the HL-LHC FRAS [8].

The architecture combines a DI/OT-compatible main board based on a Raspberry Pi Compute Module 5, a dedicated sensor emulator and off-the-shelf USB oscilloscopes to provide comprehensive coverage of digital interfaces and analogue front-end behaviour.

The system significantly reduces operator intervention compared to the previous manual bench, while improving repeatability, test coverage and traceability through integration with CERN's EAM and EDMS infrastructures.

Future work will focus on refining the emulator for on-site cable validation use and tightening automated diagnosis of specific hardware issues to further accelerate commissioning of the HL-LHC alignment system.

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