Development of a Modular Gas Monitoring System (GMS) for Real-Time Quality Assessment in Gaseous Radiation Detectors

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Abstract

We present the development and characterization of a Gas Monitoring System (GMS) designed for real-time gas quality assessment in gaseous radiation detectors. The system monitors critical parameters including humidity, oxygen concentration, pressure, and flow rate, which are essential for optimal detector performance and longevity. The GMS utilities a Raspberry Pi 5-based architecture with InfluxDB for data storage and Grafana for visualization, providing a standalone, portable solution for research and development laboratories as well as test beam facilities. Comprehensive experiments were performed for the chosen sensors, to ensure reliable readouts including flow sensor calibration table for popular gas mixtures, revealing the necessity of gas-specific calibration factors. The system demonstrates reliable performance with ppm oxygen detection, ppm-level humidity monitoring, and pressure measurements. The complete system is available as an open-source project with detailed documentation, assembly instructions, and production files, making it accessible to the broader detector physics community within the DRD1 collaboration framework. The total system cost remains within 5,000 CHF, making it accessible to research groups worldwide.The complete system is shown in Fig. 5.

Keywords: Gas monitoring, Gaseous detectors, DRD1 collaboration, Real-time instrumentation, Open source hardware, Flow sensor calibration

1. Introduction

Gaseous radiation detectors play a crucial role in high-energy physics experiments and applications beyond fundamental research, offering excellent readout granularity, timing resolution, and scalability to large active areas [1]. These detectors can operate effectively in high-rate environments and demonstrate remarkable resilience to radiation damage. However, their performance is critically dependent on the quality and purity of the gas mixtures employed.

The quality and cleanliness of gas mixtures are of paramount importance for optimal detector performance and must therefore be continuously monitored and assured. For instance, even minimal oxygen contamination can significantly compromise detector performance, leading to significantly reduced operational efficiency and measurement accuracy [2] as shown in Figure 1. Beyond achieving optimal performance, maintaining clean gas mixtures is essential for minimizing detector aging during prolonged operation periods.

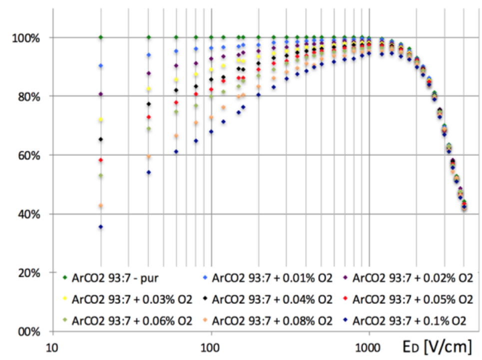

Figure 1: Fraction of non attached electrons after 5mm drift in Ar:CO_2 (93:7) with different levels of O_2 contamination.Adapted from [2], © author Fabian Kuger

The DRD1 Collaboration unites institutes working on various gaseous detector technologies, including MicroPattern Gaseous Detectors (MPGDs), Resistive Plate Chambers (RPCs), and wire-based detectors. High-quality gas mixtures represent a common interest across all detector technologies, making gas purity monitoring essential regardless of the specific detector implementation.

This report describes the development of a universal monitoring system designed for use by DRD1 member

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institutes in gaseous detector research and development activities. The system focuses on measuring humidity and oxygen concentrations in the gas mixture due to their severe influence on detector performance and ageing, along with gas pressure, gasflow, environmental pressure, environmental temperature and environmental humidity.

2. System Design and Architecture

2.1. Core Design Principles

The Gas Monitoring System (GMS) was designed based on several core assumptions derived from common operational requirements in gaseous detector applications:

- Most detectors operate under slight overpressure with constant gas flushing
- Sensors should be connected in-line to the detector gas line at the exit point
- The system must be portable and suitable for both laboratory and test beam environments
- Total system cost should remain below 5,000 CHF
- Complete open-source documentation and ease of replication are essential

2.2. Hardware Architecture

The system architecture centres around a Raspberry Pi 5 (RPI5) platform running InfluxDB for data storage and Grafana for visualisation and user interface (Figure 2). This configuration provides a standalone system utilising an RPI SSD kit for reliable data storage.

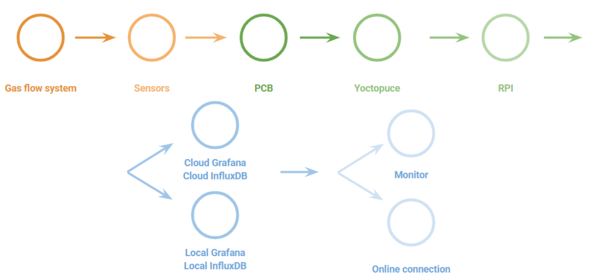

Figure 2: Overall system architecture showing data flow from sensors through Yoctopuce modules to the Raspberry Pi 5 platform with InfluxDB storage and Grafana visualisation.

Sensor integration utilises Yoctopuce modules connected via a YoctoHub-USB to the RPI5, providing reliable analogue-to-digital conversion and standardised communication protocols. The system monitors the following gas parameters:

- Gas pressure (differential measurement)
- Humidity (dew point measurement)
- Oxygen concentration (zirconia sensor)
- Flow rate (thermal mass flow principle)
- Environmental parameters (temperature, atmospheric pressure, ambient humidity)

2.3. Software Implementation

The software stack consists of InfluxDB 1.x for time-series data storage, Grafana for real-time visualisation and alerting, custom Python scripts for sensor data acquisition, and automated system startup and configuration scripts. All software components run locally on the RPI5, ensuring system autonomy.

3. Sensor Selection and Characterisation

3.1. Humidity Sensor (DMT143)

The humidity monitoring utilises a Vaisala DMT143 dew point sensor with operating range from −80°C to +20°C dew point (0 to 29,143 ppm), resolution of ±2°C, and working principle based on a thin-film polymer capacitor whose capacitance changes as it absorbs or releases water vapor, allowing dew point measurement [3].

3.1.1. Calibration Test of the Vaisala DMT143 Humidity Sensors

Objective. To assess the measurement consistency of two nominally identical Vaisala DMT143 humidity sensors after observing discrepant readings under comparable operating conditions.

Experimental setup. The experiment comprised two parts, conducted at room temperature with clean gas lines and regulated flow:

Part I:

(i) Sensor A was connected to a dry Argon line at a low flow rate of $3\,\mathrm{L\,h^{-1}}$ for 2 h.

(ii) Sensor A was then replaced by Sensor B under the same conditions (Argon, $3\,\mathrm{L\,h^{-1}}$, 2 h).

Part II:

(i) Sensors A and B were connected in series to a clean Argon line while sweeping the flow from $3\,\mathrm{L\,h^{-1}}$ to $7\,\mathrm{L\,h^{-1}}$ over 3 h.

(ii) Subsequently, one sensor was connected to a CO_2 line for 3 h at the same flow rate, then reconnected to the Argon line and monitored for re-stabilization.

Result interpretation and dew-point conversion. For clarity, moisture levels are reported both as dew point (DP) and as volumetric concentrations in ppm. To this end, we employed a modified Magnus–Tetens formulation in which the constants are adjusted such that the saturation vapor relation yields directly

$$x_{H_2O}(T_{DP})\,[\mathrm{ppm}] = 6295.47 \cdot 10^{\frac{9.5\,T_{DP}}{265.5+T_{DP}}}, \qquad (1)$$

with T_{DP} in °C. This empirical variant is consistent with the standard Magnus approximation for $p_{sat}(T)$, but re-parameterized to return the water vapor fraction in ppm as a function of the dew point.

Results.

(1) **Part I (Argon, 3 L h^{-1}).** During the first 2 h, the two sensors reported ~6000 ppm and ~8000 ppm, respectively, corresponding to distinct dew points $T_{DP,A}$ and $T_{DP,B}$ (see Table 1). The difference is consistent with the device DP accuracy on the order of ±2.00 °C when propagated through in Eq. 1.

(2) **Part II (Argon, 3 L h^{-1} to 56 L h^{-1}).** In the initial ~2 h, readings differed (representatively, ~75 ppm vs. ~5 ppm), with corresponding dew points $T_{DP,A}$ and $T_{DP,B}$. As the flow increased from 3 L h^{-1} toward 5 L h^{-1}, the inter-sensor differential in ppm (and equivalently in DP) monotonically decreased, indicating improved equilibration and reduced sampling bias at higher purge rates. Thereafter, both sensors converged to ~75 ppm (T_{DP} equal within uncertainty) and remained stable. A temporary exposure of one sensor to CO_2 did not produce a lasting offset; upon reconnection to Argon, instantly the reading re-converged to ~75 ppm and the corresponding DP.

Conclusion. A stabilization window exceeding ~2 h is advisable before interpreting quantitative results under low-flow, dry-gas conditions. Increasing the purge flow from 3 L h^{-1} to 5 L h^{-1} reduces inter-sensor differentials (in both ppm and dew point), consistent with improved mixing and equilibration. While the DMT143 DP accuracy (order ±2 °C) can map to sizable relative differences in ppm at higher moisture, under typical operating conditions of continuously purged lines at ≥4 L h^{-1} the measurement stability and accuracy are sufficient for this study.

3.2. Flow Sensor (D6F-P0010A1)

Flow measurement employs the Omron D6F-P0010A1 thermal mass flow sensor with range 0–60 L h^{-1}, resolution 0.4%, and working principle based on differential thermal conductivity measurement. The sensor operates by measuring the temperature difference between upstream and downstream thermocouples positioned around a heating element. Due to the thermoconductivity of the gas flowing through the system, the thermocouple downstream heats more than the thermocouple upstream, creating a potential difference that the sensor measures and converts to flow rate [4].

3.2.1. Flow Sensor Calibration Study

Objective: The purpose of this study was to determine the gas-specific response characteristics of the Omron flow sensors (D6F-P0010A1, D6F-0001A1) under different detector gas mixtures.

Experimental setup: eight common gas mixtures were tested. Two mixers were employed: large mixer dedicated to mixtures containing R-134a and the other to mixtures based on pure Argon. The calibration setup consisted of a mixer connected to a clean stainless steel gas line, followed by a plastic pipe into the sensor and a two-metre plastic output pipe.

For the large mixer, the calibration time between successive flow settings was 2 hours. After reaching a stable signal, the output voltage was recorded for 20 minutes. For the small mixer, the system response to changes in flow was essentially immediate; nevertheless, a 20-minute waiting period was applied prior to recording the measurement.

The flow was initially set to 10 L h^{-1} and reduced by 1 L h^{-1} every 20 minutes. The minimum time between changing gas mixtures was 2 hours to ensure purity of the mixture.

For the analysis, When a dedicated coefficient for a given gas mixture was not available, we computed an effective coefficient by a linear mixing rule. For a mixture with components $i = 1, \ldots, n$ having volumetric fractions y_i ($\sum_i y_i = 1$) and online pure–gas coefficients C_i (from MKS/FLUIDAT), as presented in Table 2, the mixture coefficient is

$$C_{mix} = \sum_{i=1}^{n} y_i\, C_i.$$

Fractions y_i are volume fractions (For the polynomial fit, the rule is applied coefficient–wise, e.g., $a_{mix} = \sum_i y_i a_i$, $b_{mix} = \sum_i y_i b_i, \ldots, f_{mix} = \sum_i y_i f_i$.

Table 1: Summary of calibration measurements for Sensors A and B in Argon.

	Condition	Flow (L/h)	A (ppm)	B (ppm)	Δ (ppm)	$T_{DP,A}$ (°C)	$T_{DP,B}$ (°C)	ΔT_{DP} (°C)
Part I	Ar pre-stab.	3.00	6000.00	8000.00	2000.00	−19.30	−16.90	2.40
Part II	Ar, early	5.00	75.00	6.00	69.00	−44.70	−59.80	−15.10
	Ar, sweep	5.00	differential decreases with flow	same trend in DP				
	Ar, stable (5L/h)	5.00	75.00	75.00	0.00	−44.70	−44.70	0.00
	Ar, stable (6L/h)	6.00	37.00	37.00	0.00	−50.50	−50.50	0.00
	Ar, stable (7L/h)	7.00	9.00	9.00	0.00	−61.40	−61.40	0.00

Notes: (i) T_{DP} values calculated using Eq. 1 at recorded T_{gas} and P_{tot}. (ii) After temporary exposure of one sensor to CO_2 and reconnection to Argon, both sensors showed consistent readings across different flow rates before stabilizing at ~75 ppm at 5 L/h with ΔT_{DP} = 0.

Results: The output voltage of the sensors was recorded as a function of flow rate for each gas mixture. Representative calibration curves are shown in Fig. 3 and Fig. 4, and raw data are summarised in The full voltage readout tables are provided as Supplementary Table S1 (CSV) for reproducibility. Data analysis followed the Omron datasheet fitting procedure: a linear fit for the D6F-P0001A1 and a fifth-degree polynomial fit for the D6F-P0010A1 [5]:

$$V_{out} = a_0 + a_1 F + a_2 F^2 + a_3 F^3 + a_4 F^4 + a_5 F^5, \quad (2)$$

where V_{out} is the sensor output voltage and F is the flow rate in $\mathrm{L\,h^{-1}}$. The fitted parameters for each mixture are presented in Table 3. Inspection of the attached CSV reveals that the linear Omron D6F-P0001A exhibits early saturation at very low flow rates (below 3.00 L/h) and does not perform adequately with the common gas mixtures employed in gaseous detectors; consequently, it is not considered in the subsequent analysis.

Conclusion: The calibration study showed that the conversion between flow and voltage is not solely determined by the thermal conductivity properties of the individual gases. Instead, the response is influenced by interactions within the gas mixtures and potentially by additional unknown parameters. Consequently, calibration factors obtained from Fluidat [6] or MKS [7] should not be applied directly to Omron sensors. We recommend using the fit formulae obtained in this work (Table **??**) for the tested mixtures. For any other gas mixture, a dedicated calibration experiment should be performed, and results should be shared in the repository for collective use.

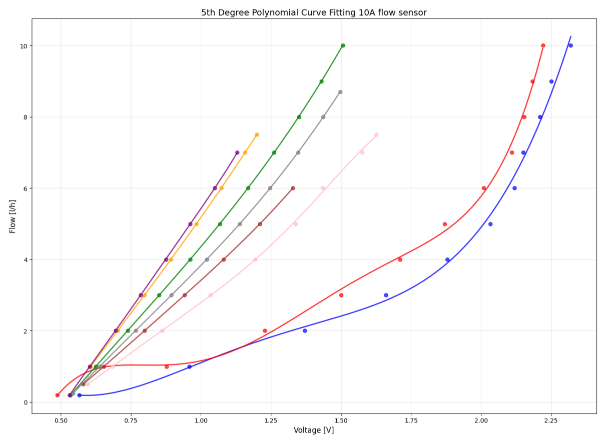

Figure 3: Experimental calibration of the D6F-P0010A flow sensor using fifth-order polynomial fitting of the voltage–flow response, extended to eight gas mixtures beyond the manufacturer's air-based calibration.

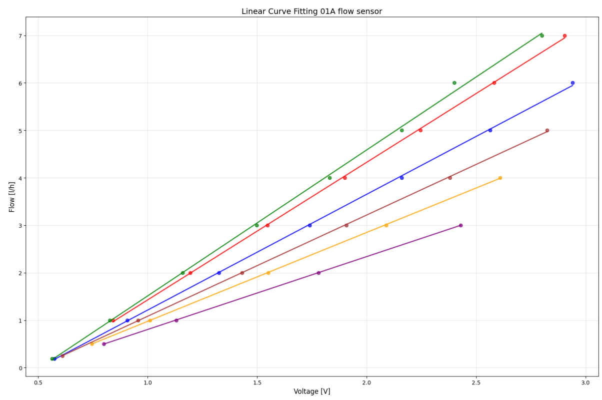

Figure 4: Experimental calibration of the D6F-P0001A linear flow sensor: voltage–flow response evaluated across eight gas mixtures.

3.3. Oxygen Sensor (Senz-Tx Zirconia)

Oxygen concentration monitoring utilises a Systech Senz-Tx Zirconia electrochemical sensor with range 0–

Table 2: Online results for calibration factor for gas vs experiment results on Omron sensor D6F-P0010A1.

Gas Mixture	MKS	FLUIDAT	Experiment	$\|\Delta\|$ MKS vs Exp [%]	$\|\Delta\|$ FLUIDAT vs Exp [%]
95.2% R-134a + 4.5% i-C4H10 + 0.3% SF6	0.35	0.36	0.63	45.30	42.80
64% R-134a + 30% CO_2 + 5% i-C4H10 + 1% SF6	0.45	0.47	1.42	68.40	66.80
70% Ar + 30% CO_2	1.18	1.20	0.37	224.20	229.70
93% Ar + 7% CO_2	1.34	1.36	0.72	86.80	88.70
45% Ar + 15% CO_2 + 40% CF_4	0.90	0.92	0.88	1.70	3.80
40% Ar + 50% CO_2 + 10% CF_4	0.95	0.97	0.47	103.80	109.40
80% Ar + 20% CF_4	1.20	1.21	0.59	102.40	104.70
100% Ar	1.39	1.40	1.53	8.90	8.10

Table 3: Recommended Fitting Coefficients for Common Gas Mixtures Using D6F-P0010A Flow Sensor in Gas Detection Applications.

Gas Mixture	**a**	**b**	**c**	**d**	**e**	**f**
95.2% R-134a + 4.5% i-C_4H_{10} + 0.3% SF_6	−0.01	0.12	−0.48	0.79	−0.52	0.12
64% R-134a + 30% CO_2 + 5% i-C_4H_{10} + 1% SF_6	0.20	−1.26	3.13	−3.65	2.02	−0.41
70% Ar + 30% CO_2	0.05	−0.02	0.07	−0.12	0.22	−0.09
93% Ar + 7% CO_2	0.06	−0.29	0.62	−0.63	0.48	−0.15
45% Ar + 15% CO_2 + 40% CF_4	−0.18	0.89	−1.74	1.62	−0.64	0.08
40% Ar + 50% CO_2 + 10% CF_4	−0.10	0.10	−0.26	0.29	−0.04	−0.03
80% Ar + 20% CF_4	−0.05	0.26	−0.49	0.41	−0.03	−0.04
100% Ar	0.75	−3.03	4.60	−3.76	1.64	−0.32

1000 ppm, resolution 1 ppm, and working principle based on electrochemical zirconia cell measurement. The sensor is not compatible with flammable gases or aggressive substances (Cl_2, F_2, HCl, HF, Si compounds) [8].

3.4. *Pressure Sensors*

Two pressure sensor options are available:

1. TE Connectivity CTEM7N010GQ4 (production discontinued): Range ±10 mbar, Resolution 0.2%
2. Danfoss MBS 9200 (new sensor, still under evaluation): Range ±20 mbar, Resolution 0.2%

3.5. *Environmental Sensor (Yocto-Meteo-V2)*

Environmental monitoring capabilities utilise the Yocto-Meteo-V2 sensor including [9]:

- Temperature: −40°C to +125°C, ±0.2°C accuracy
- Atmospheric pressure: 0.3–1.1 bar, ±0.01 mbar resolution
- Ambient humidity: 0–80% RH, ±1.5% RH accuracy

4. Mechanical Design and System Integration

4.1. *Mechanical Design*

Overview: The system is housed in a Pelican iM2275 case, offering portability, robustness, and environmental protection. The case's external dimensions are 38.7 × 39.4 × 26.0 cm [10].

Component Layout: Mechanical parts are mounted to the bottom (base) of the case, while the electronics are fastened to the lid. The lid incorporates a touch display, and the environmental sensor protrudes through the top of the lid to allow direct exposure to ambient air for measurement purposes.

Access Ports: The case is equipped with four through-holes for interfacing:

- Bottom: gas line inlet
- Bottom: gas line outlet
- Bottom: power connector
- Lid: environmental sensor housing

4.2. *Gas Line Integration*

The sensor arrangement was chosen to secure the lowest risk of gas pollution. The flow sensor – containing

Figure 5: The GMS system, fully assembled.

plastic components – was connected last, while the oxygen sensor that requires a bypass and therefore multiple connectors was positioned second-to-last, according to the schematics in Fig. 6.

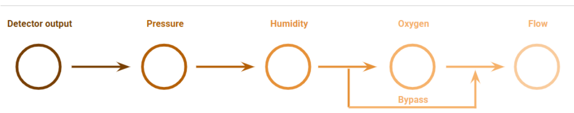

Figure 6: The GMS system piping schematics.

The sensors were located vertically according to producer recommendations. The pipe mechanism was designed using straight stainless steel pipes and Swagelok connectors only, for unity in the production of the systems and clear assembly process.

4.3. *System Validation Tests*

4.3.1. *Test-Beam Prototype Evaluation*

Objective: To assess the prototype's usability and data-acquisition performance in a test-beam environment, including user interaction and integration with a beam telescope.

Experimental setup: The system was deployed at the test beam and connected to the detector on its exhaust (output) line. Power was supplied from the local facility,

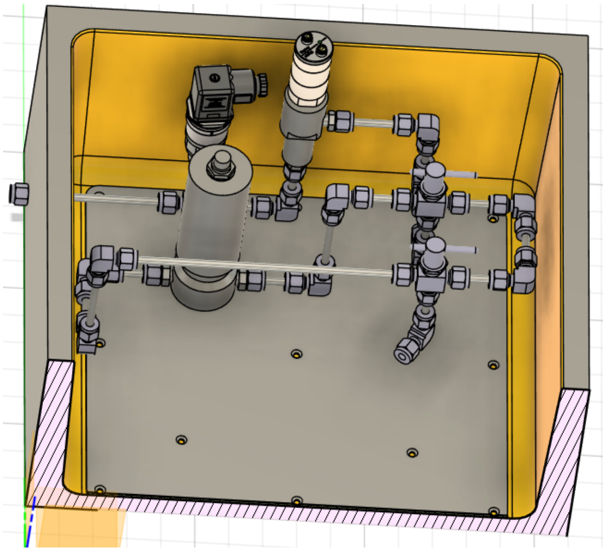

Figure 7: Mechanical assembly showing sensor positioning and gas line configuration. All connections use stainless steel tubing and Swagelok fittings for consistency and reliability.

and the readout software was executed on a laptop. (see also Fig. 8).

Results: The system was recognized immediately and produced valid data without additional configuration. End-to-end integration and bring-up time—from physical connection to stable data streaming—was approximately 5 minutes. Following deployment, the system operated continuously and stably for four days, delivering uninterrupted data until it was intentionally disconnected from the experimental setup.

Conclusion: The mechanical and software design supports rapid deployment and routine daily use under beam conditions. The system satisfies the project requirements for portability and ease of operation, including reliable performance in a test-beam environment and sustained multi-day operation.

4.3.2. *System Pressure Test*

Objective: The aim of this test was to evaluate the effect of connecting the system on the gas pressure inside the detector.

Experimental setup: A pressure sensor was connected at the inlet of the system, which was supplied with a standard Ar–CO_2 (70:30) gas mixture at a flow rate of $5\,\mathrm{L\,h^{-1}}$. Each component of the system was subsequently disconnected in sequence, with a 10-minute interval between disconnections.

Results: During the entire procedure, pressure fluctuations remained below 0.1 mbar.

Conclusion: The system does not contribute to an increase in the gas line pressure; in other words, connecting

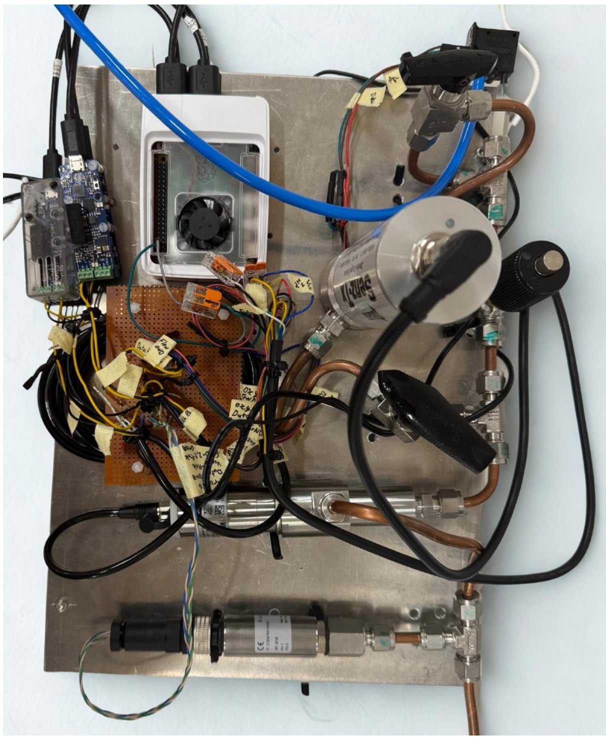

Figure 8: Prototype of GMS deployment examples showing laboratory installation and test beam configuration demonstrating system versatility and portability.

the system to the gas line does not effectively raise the pressure inside the detector.

5. Electronics and Power Management

The electronic subsystem is responsible for real-time acquisition of sensor signals, their analogue-to-digital conversion via dedicated Yoctopuce modules, and subsequent data transfer through a USB hub to the Raspberry Pi 5. The processed information is then displayed on the integrated monitor.

5.1. Custom PCB Design

A custom printed circuit board (PCB) was developed to distribute power to all electronic components and interface the analogue sensor signals with Yoctopuce acquisition modules. The design followed three core principles:

1. Electrical safety
2. Ease of assembly
3. Use of off-the-shelf components

The system is supplied with 24 VDC, which powers the current-type sensors (pressure, humidity, and oxygen). A DC–DC converter with a trim-up option regulates the voltage to 5.1–5.2 V, supplying the flow (voltage-type) sensor, the display, and the Raspberry Pi 5 via its

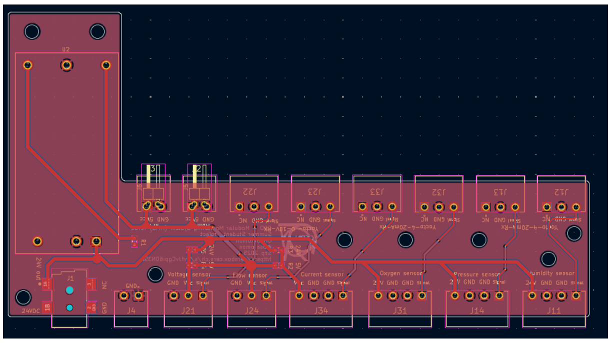

Figure 9: Custom PCB schematic showing power distribution, sensor interfaces, and expansion options.

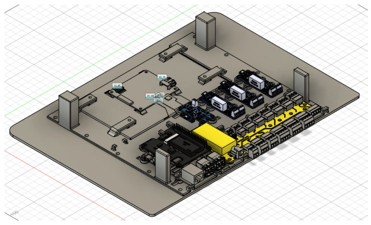

Figure 10: Schematic design and integration of all electrical components in the GMS.

GPIO pins. The output adjustment to 5.2 V was implemented using a 63.4 kΩ resistor, as specified in the converter datasheet.

The PCB includes provisions for one additional current sensor and one additional voltage sensor, each selectable between 5 V and 24 V via jumper configuration. Sensors and Yoctopuce modules are connected through quick connectors to ensure secure wiring and mechanical robustness.

5.2. Power Supply Configuration

Mains power is supplied through a C14 connector (220 VAC). A switching power supply converts 220 VAC to 24 VDC, which feeds both the sensors and the PCB.

5.3. Electronic Enclosure

The electronic subsystem is housed in a custom 3D-printed enclosure designed for the Bambu X1C printer (build volume: 260×260 mm). The enclosure was optimised as a single-part design to minimise support structures and reduce printing time, while integrating mounting features for mechanical stability.

6. Software Implementation and User Interface

6.1. Data Acquisition and Storage

Sensor signals are transmitted via the Yoctopuce USB-hub to the Raspberry Pi (RPI), which serves as the central processing unit of the system. The acquired data

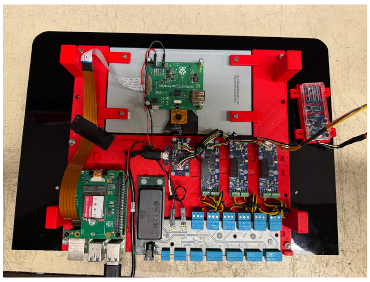

Figure 11: 3D-printed enclosure design optimised for single-part manufacturing with integrated mounting features (Bambu X1C specifications).

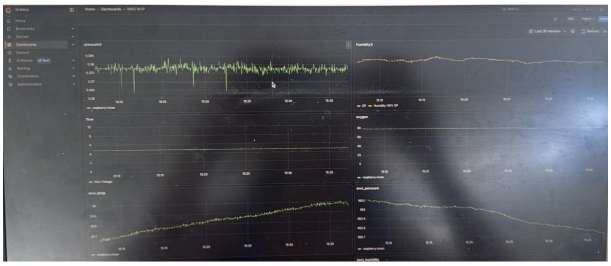

Figure 12: Grafana dashboard showing real-time gas monitoring parameters with trend analysis and alarm indicators for comprehensive system oversight.

are stored locally on the RPI using a dedicated SSD module, and are subsequently managed through the InfluxDB database. This platform is optimised for time-series data management, enabling efficient handling of high-frequency measurements and the application of configurable retention policies.

The system is configured to initialise automatically upon power-up, ensuring continuous monitoring with minimal user intervention. For flow measurements, the user is required to select the appropriate gas mixer from a predefined list, after which the corresponding sensor data are recorded and stored in the database.

6.2. *Grafana Dashboard Configuration*

Visualisation and analysis of the collected data are facilitated by Grafana, which is integrated both locally on the RPI display panel and remotely via network access. The Grafana interface provides comprehensive functionality, including real-time parameter monitoring, historical trend analysis, definition of alarm thresholds, multi-user access control, and data export options for further processing.

All measurement data can thus be accessed either directly on the system's display or online, provided the user is connected to the same local network as the RPI. This dual accessibility ensures both immediate on-site feedback and remote supervisory control capabilities.

Table 4: System performance summary showing achieved specifications for all monitored parameters

Parameter	Range	Resolution
Humidity	0–29,143 ppm	±2°C dew point
Oxygen	0–1000 ppm	1 ppm
Pressure	±20 mbar	0.04 mbar
Flow	0–60 $\mathrm{L\,h^{-1}}$	0.24 $\mathrm{L\,h^{-1}}$

Users access the interface via web browser connection to the RPI5's IP address.

7. Performance Evaluation and Results

7.1. *System Performance Summary*

The system was performed in experiments to obtain the reliability of the results in pressure and humidity. The flow sensor was experimented upon to find the fitting function for popular gas mixtures for gas detectors. Comprehensive testing demonstrated reliable performance across all monitored parameters with specifications meeting or exceeding design requirements.

7.2. *Field Deployment Results*

The GMS is currently being used at GDD and Gas group as part of DRD1 collaboration for laboratory detector development activities and test beam measurement campaigns.

8. Cost Analysis and Open Source Implementation

8.1. *System Cost Analysis*

The system will be estimated under 1,500 €for the electronics and mechanics, €5,000 in total, including the sensors cost. The complete system cost demonstrates achievement of the sub-€5,000 target, making the technology accessible to research groups worldwide.

8.2. *Documentation and Community Contributions*

The project is well-documented as open source on GitLab, and easy to pull and copy to other devices. The documentation include [11]:

- Full 3D design of the system
- Production files
- Bill of Materials (BOM) with links for purchases
- Assembly instructions

- System image for deployment
- User manual: System usage, instructions for installing local software, and sensor integration guidelines.

The open-source nature encourages community contributions, particularly additional gas mixture calibration data, alternative sensor integration options, software enhancements, and documentation improvements.

9. Recommendations for Future Work

1. **Quantify system-induced humidity**
   - *Objective:* Determine the net moisture contribution of the measurement chain (tubing, valves, fittings, sensors).
   - *Method:* Install external humidity probes at the gas-line inlet and outlet of the system under representative operating conditions (gas composition, flow, and pressure). Perform step tests at multiple purge rates (e.g., $3.00\,\mathrm{L\,h^{-1}}$, $6.00\,\mathrm{L\,h^{-1}}$ and $10.00\,\mathrm{L\,h^{-1}}$), logging inlet/outlet dew point (or ppm) synchronously.
   - *Deliverables:* (i)Transfer function $\Delta T_{\mathrm{DP}} = T_{\mathrm{DP,out}} - T_{\mathrm{DP,in}}$ (and the equivalent Δppm) versus flow; (ii) time constants for moisture equilibration; (iii) uncertainty bounds.
2. **System-level accuracy verification with reference mixtures**

   Although the sensors discussed routinely employ GDD and Gas group, these are typically used independently. We therefore recommend assessing the reliability and accuracy of the sensors as an integrated system.

   - *Objective:* Assess the accuracy of all integrated sensors (oxygen, flow, pressure, humidity) when operated as a coupled system.
   - *Method:* Feed certified gas mixtures with known O_2 fraction, controlled flow, pressure, and humidity setpoints. Use traceable reference instruments to provide ground truth.
   - *Deliverables:* (i) Bias and precision for each sensor channel across a matrix of setpoints; (ii) a consolidated uncertainty budget including coupling effects; (iii) updated acceptance criteria and calibration intervals for field operation.
3. **Extend the flow-sensor calibration to additional gas mixtures**
   - *Objective:* Reduce composition-dependent error by characterizing the flow transducer in relevant gas mixtures used in operation.
   - *Method:* Expand the current calibration table to include multiple mixtures, spanning the operational flow range using the Omron sensor.
   - *Deliverables:* (i) Updated calibration coefficients/tables per mixture; (ii) validated fit to the Omron sensor.
4. **RPI EM interference inspection**
   - *Objective:* The Raspberry Pi can act as a source of electromagnetic interference (EMI) that perturbs the oscilloscope's measurement of the detector signal.
   - *Method:* We therefore recommend accounting for this effect in the experimental layout and evaluating mitigation strategies—such as increased spatial separation, shielding and proper grounding, differential (twisted-pair) cabling with ferrite chokes.

10. Discussion and Conclusions

We developed a portable, standalone Gas Monitoring System (GMS) for real-time quality assessment of detector gas lines within the DRD1 collaboration, targeting R&D laboratories and test-beam areas. The system measures line parameters—pressure, humidity (dew point), oxygen, and flow—alongside ambient temperature, pressure, and humidity, using off-the-shelf components and standard fabrication methods (3D printing, laser cutting, soldering). The total build cost is sub-€5,000.

10.1. Key outcomes

- **Validated performance in lab and beam:** The prototype integrated with a beam telescope and delivered stable, uninterrupted data for four days in a test-beam deployment, with ~5 min bring-up time.
- **Calibration that matches use conditions:** Flow-sensor characterisation showed gas-dependent response; universal calibration factors are insufficient across mixtures, and a fitting table was built for popular gas mixtures. Dew-point accuracy effects explain apparent ppm differences at low flows; stability improves at $\geq 4\,\mathrm{L\,h^{-1}}$.

- **Modular, reproducible design:** The architecture supports rapid adaptation to different detector technologies and local constraints while remaining cost-effective and easy to deploy.

- **Open, collaborative path to adoption:** Complete open-source documentation enables replication and extension within DRD1 and the wider gaseous-detector community.

10.2. Practical guidance

- **Deployment:** Place the unit to minimise electromagnetic interference (EMI) with sensitive read-out (oscilloscopes, preamps). Prefer differential cabling, proper grounding, and optional shielding. Use instruction files from [11].

- **Operation:** Use purge flows of $\geq 3\ \mathrm{L\,h^{-1}}$ to reduce inter-sensor differentials and shorten equilibration. Allow $\gtrsim 2$ h for stable humidity readings after major changes (gas, plumbing, or flow).

- **Calibration:** Calibrate flow in the intended gas mixture(s); store per-mixture coefficients.

- **System checks:** Check for leaks before deployment.

10.3. Concluding statement.

The GMS provides reliable, accurate monitoring of humidity (dew point), oxygen, pressure, and flow for gaseous detectors, with demonstrated robustness in both laboratory and beam environments. Its modular hardware, documented calibration procedures, and open-source implementation make it a practical instrument for safeguarding gas quality and extending detector lifetimes across institutions. Ongoing community contributions within DRD1 will further refine calibration libraries, automation, and usability.

Acknowledgements

I would like to express my sincere gratitude to my supervisors, Gianluca Rigoletti and Florian Brunbauer, for their guidance and mentorship at every stage of this work. I am grateful to Miranda Van Stenis, the laboratory technician, for her invaluable assistance in building the system, and to Stefania Juks for her guidance during the laboratory experiments. I also thank all colleagues in the GDD and Gas Group for their support and collaboration. This work was made possible by the CERN Summer Student Programme, which enabled me to engage with CERN's exceptional concentration of expertise, and by Ben-Gurion University of the Negev in Israel for facilitating my participation during my studies.

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