NDIR Optical E-Nose for Contactless Diabetes Monitoring and Diagnosis: An integrated HW-AI Framework

NDIR Optical E-Nose for Contactless Diabetes Monitoring and Diagnosis: An integrated HW-AI Framework

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***Abstract*—Non-invasive and widely accessible methods for Diabetes Mellitus (DM) screening and monitoring are crucial to address the limitations of conventional blood-based assays. Exhaled breath (EB) analysis provides a contactless, real-time alternative by detecting disease-associated changes in Volatile Organic Compounds (VOCs). This PhD research work introduces a compact Non-dispersive Infrared (NDIR)-based optical Electronic Nose (E-nose) for rapid VOCs detection. Preliminary laboratory tests using a general-purpose IR sensor and a MEMS IR emitter showed feasibility for detecting low VOCs concentrations. Expanding the system with nonspecific near-/mid-IR, MOS, and ambient sensors could further enhance performance, enabling AI-driven multi-modal strategies for DM-oriented breath analysis.**

***Index Terms*—Diabetes monitoring, Contactless sensing, AI platform, IR Breath Analysis, Biomedical Sensors**

I. INTRODUCTION

Diabetes Mellitus (DM), a chronic disorder of insulin production/action, affects hundreds of millions globally (nearly half undiagnosed), with early detection and monitoring critical to prevent severe complications [1]. Traditional blood-based diagnostics, such as finger-prick glucose and HbA1c tests, are invasive and inconvenient, motivating non-invasive approaches [1]. Exhaled Breath (EB) analysis enables contactless monitoring by detecting Volatile Organic Compounds (VOCs) linked to metabolic processes, including acetone (main DM biomarker) isoprene, ethanol, isopropanol, ammonia, and sulfur-containing compounds, which can be analyzed in clusters to improve diagnostic accuracy and reduce individual variability [2], [3], [4], [5]. Detection methods range from highly sensitive but bulky mass-spectrometry techniques, namely Gas Chromatography (GC–MS), Proton Transfer Reaction (PTR–MS), Selected Ion Flow Tube (SIFT–MS), to portable chemical sensors (MOS, electrochemical), which are rapid but limited in selectivity and affected by cross-sensitivity [2]. Among Infrared (IR)-based methods, Non-Dispersive Infrared (NDIR) spectroscopy provides the best balance between cost, specificity, and portability, though challenges remain regarding water interference and sensitivity [2].

This research work, conducted as part of a PhD project, presents a compact NDIR-based optical Electronic Nose (E-nose) for rapid, non-invasive detection of DM-related VOCs in EB (Figure 1), suggesting promising results. Further integration of near-/mid-IR, MOS, and ambient sensor data would support an AI-based multi-modal platform that leverages both spectroscopic specificity and E-nose versatility, enabling data-driven approaches for enhanced, contactless, real-time DM monitoring and diagnosis. As a proof-of-concept, this work demonstrates preliminary system behavior, assessing feasibility for detecting low VOCs concentrations under controlled laboratory conditions.

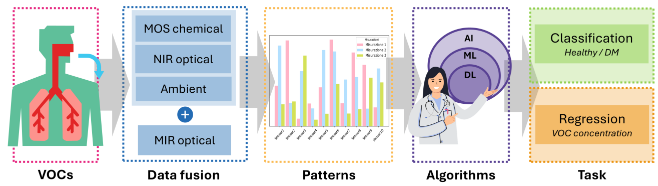

Fig. 1. Framework pipeline for non-invasive DM assessment

II. MATERIALS & METHODS

The developed system employs a MEMS IR source (EMIRS200, Axetris) operating over 2–14μm and driven at 50Hz with a 62% duty cycle, together with a general-purpose Thermal MOS (TMOS) sensor (STHS34PF80, STMicroelectronics) covering 5–20μm and originally intended for presence detection, providing an effective 1Hz output through the averaging of 128 samples per measurement [6]. Both components are integrated in a modular, 3D-printed Polyamide12 (PA12) chamber featuring vapor-smoothed walls to increase reflectivity and reduce material porosity. The chamber (23.5mm internal diameter, 10cm path length, 43.37mL volume, with $\tau\approx$6.5s when flow=400mL/min) is housed in aluminum-coated boxes to reduce both environmental and electrical noise. Controlled

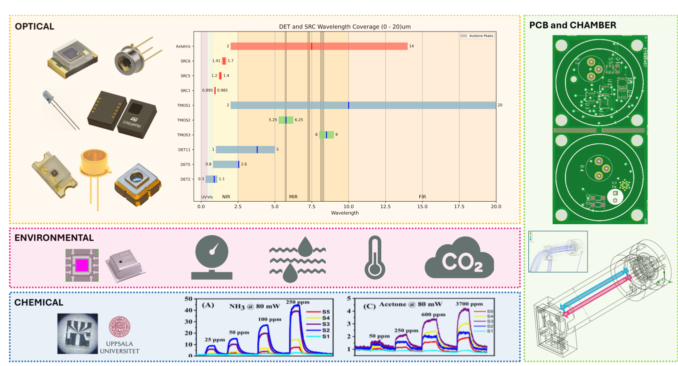

Fig. 2. Multi-modal platform for VOCs detection

TABLE I
MFC SETTINGS FOR CONTROLLED VOCS INJECTION

VOCs	Gas [ppm]	Base	C [ppm]	Flow [SCCM]	T G/A [s]
C_3H_6O	1000	O_2, N_2	500, 100, 10	500	41/62
NH_3	1000	N_2	400, 200, 100	400	200/800
H_2S	500	N_2	225, 100, 50	400	500/1000

VOCs - i.e. Acetone (C_3H_6O), Ammonia (NH_3), Hydrogen Sulfide (H_2S) - were injected via Mass Flow Controller (MFC) (Table I) at 1.5bar, alternating with clean air, without temperature or humidity control (T_{amb} 21–23°C, RH_{amb} 20–50%). TMOS signals were smoothed (moving average, M=50) and segmented by response and recovery windows.

III. RESULTS

Window-related data are used to compute the relative response

$$S\% = \frac{R_O - R_G}{R_O} \times 100$$

which compares gas-exposure output (R_G) to baseline (R_0), quantifying absorption at the target wavelength and providing a standardized metric of sensitivity, linearity, and reproducibility across gases (Figure 3). H_2S produced the strongest response (2.31% at 225ppm), exceeding C_3H_6O (1.66% at 500ppm) and NH_3 (0.67% at 400ppm); at equal concentrations (100ppm), the trend persisted (0.81%, 0.55%, 0.30% respectively). These results indicate that the system can detect C_3H_6O and NH_3 down to 100ppm and H_2S to 50ppm, with preliminary concentration-response trends showing near-linear correlations (r=0.99 $\pm$ 0.10, R^2=0.98 $\pm$ 0.03) (Figure 3), suggesting the feasibility of the proposed system for low VOCs traces detection.

IV. DISCUSSION & FUTURE PERSPECTIVES

DM is a widespread chronic disorder causing hyperglycemia and complications, with early assessment essential for management; however, current blood-based tests are invasive and unsuitable. EB analysis offers a non-invasive alternative, but existing methods are limited by cost, size, or cross-sensitivity; In this context, NDIR spectroscopy provides the best compromise.

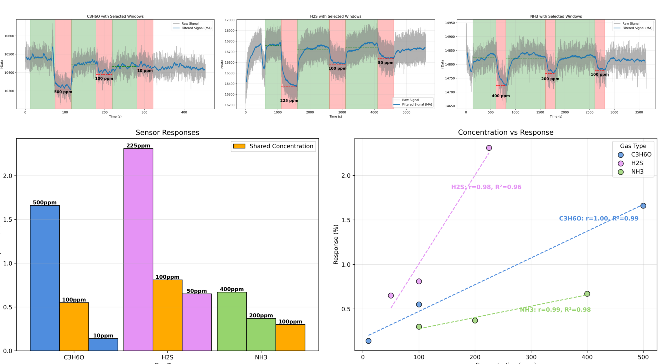

Fig. 3. Preliminary results in lab-settings for C_3H_6O (Blue), H_2S (Pink), and NH_3 (Green) respectively

This PhD research work suggests the feasibility of a compact, non-invasive NDIR-based optical E-nose for detecting DM-related VOCs in EB. Preliminary lab-experiments using a general-purpose IR sensor and a MEMS IR emitter showed reliable detection of reduced C_3H_6O, NH_3, and H_2S concentrations, showing near-linear concentration–response behavior and clear relative responses, even under early, non-optimized experimental conditions.

Limitations of the current system include inconsistencies in driving modes, chamber conditioning, and MFC timing, which reduce SNR, compromise reproducibility, and hinder comparative analysis. Future work should refine the experimental conditions, increase concentration granularity, standardize MFC protocols, employ inert chamber materials, and further characterize emitter-sensor behavior. The platform would further benefit from integrating wavelength-selective detectors (targeting C_3H_6O absorption peaks at 5.71μm and 8.2μm), broadband reference TMOS sensors (2–20μm), MOS-based chemical sensors, and auxiliary environmental monitoring (pressure, temperature, relative humidity) to form a multi-modal sensing architecture. Such enhancements would enable more robust signal extraction by isolating VOCs-related variations, mitigating water-vapor and temperature interference, and incorporating broadband IR information to improve sensitivity and specificity.

Leveraging software-driven analysis rather than relying solely on hardware specificity, these multi-modal data streams can be processed through machine-learning algorithms for both classification and regression, ultimately supporting the development of a practical, contactless, and rapid point-of-care VOCs detection system for DM monitoring and diagnosis.

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