SAFESENS – Smart Sensors for Fire Safety

First Responders Occupancy, Activity and Vital Signs Monitoring

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***Abstract* - This paper describes the development and implementation of the SAFESENS (Sensor technologies for enhanced safety and security of buildings and its occupants) location tracking and first responder monitoring demonstrator. An international research collaboration has developed a state-of-the-art wireless indoor location tracking systems for first responders focused initially on fire fighter monitoring. Integrating multiple gas sensors and presence detection technologies into building safety sensors and personal monitors has resulted in more accurate and reliable fire and occupancy detection information which is invaluable to firefighters in carrying out their duties in hostile environments. This demonstration system is capable of tracking occupancy levels in an indoor environment, as well as the specific location of fire fighters within those buildings, using a multi-sensor hybrid tracking system. This ultra-wideband indoor tracking system is one of the first of its kind to provide indoor localisation capability to sub meter accuracies with combined Bluetooth low energy capability for low power communications and additional inertial, temperature and pressure sensors. This facilitates increased precision in accuracy detection through data fusion, as well as the capability to communicate directly with smartphones and the cloud, without the need for additional gateway support. Glove based, wearable technology has been developed to monitor the vital signs of the first responder and provide this data in real time. The helmet mounted, wearable technology will also incorporate novel electrochemical sensors which have been developed to be able to monitor the presence of dangerous gasses in the vicinity of the firefighter and again to provide this information in real time to the fire fighter controller. A SAFESENS demonstrator is currently deployed in Tyndall and is providing real time occupancy levels of the different areas in the building as well as the capability to track the location of the first responders, their health and the presence of explosive gasses in their vicinity.**

Keywords - Gas Sensors; Body Area Networks; Activity Tracking; Vital Signs Monitoring; Occupancy Detection.

I. INTRODUCTION

The SAFESENS indoor first responder localisation and activity monitoring system [1] is designed based on latest available gas and activity tracking sensor technologies. It incorporates several solutions to an emergency situation including people counting for an efficient rescue operation and first responder location finding. To meet the most demanding application needs, we have designed a sensor board along with the wireless network infrastructure which is capable of delivering the next generation of safety devices. The aim of this document is to describe the indoor localisation platform of the SAFESENS project, the interconnection of the different parts of the system (SAFESENS boards, AXIS Cameras, Raspberry Pi and Server) and location calculation part of the server software. The objectives of the Tyndall National Institute (TNI) in this project, is to develop a wearable [2] indoor localization and activity monitoring system for first responders during emergency situations. In parallel, novel explosive gas sensor technologies and physiological health monitoring systems are being integrated into the fire fighters apparel to monitor their health and well-being as they are tracked through the system as presented in Figure 1.

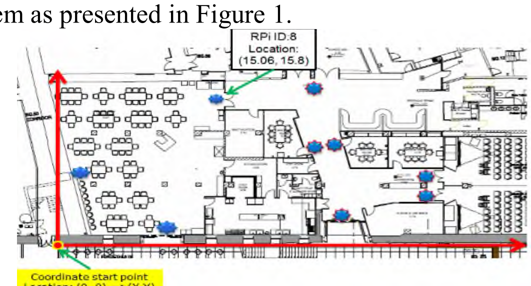

Figure 1. Deployment Area – Tyndall National Institute UCC.

This paper describes the development and validation of the SAFESENS system technologies. Section II describes the chosen architecture of the overall system. Section III describes the localization and activity tracking system development. Section IV describes the Vital signs monitoring technologies used to monitor the first responders health status. Section V describes the development of the explosive gas sensor. Section VI describes the Occupancy sensing developed in the project and the validation results are described in Section VII. Finally, conclusions and summary are contained in Section VIII

II. System Architecture

There are 8 separate system building blocks comprising the SAFESENS system: the server, mobile gateway (fire fighter's smartphone), Ultra Wide Band (UWB) localisation [3] Access Points, Raspberry Pi, Occupancy detection camera, Fire fighter tracking Node, the Physiological monitoring system and the explosive gas detector. With the implemented sensor platform, we are able to collect real time, real world data for research and analysis. The system architecture is shown in Figure 2.

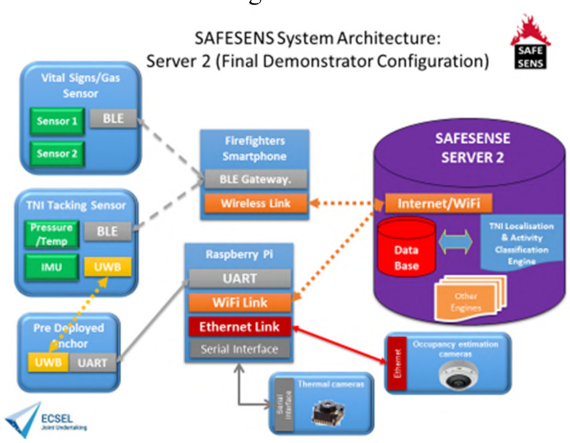

Figure 2. SAFESENS Demonstrator System Architecture.

The Smartphone carried by the firefighter acts as the integration system harvesting the sensory data sets from the firefighters apparel and sending it to the server for processing, running python based analytic/localisation engines and to facilitate visualisation of the data streams.

III. Location and Activity Tracking

A. Introduction to First Responder Activity Monitoring

A significant number of firefighters are injured every year in the line of duty [4]. Tracking firefighters while deployed in dangerous environments is critical to mitigate risk to the personnel. In large buildings, there is often a requirement to enter and deal with fires from multiple directions in order to prevent the fire from spreading. Line of sight is often obscured with smoke and debris [5] and there is also the possibility that parts of the structure may be unstable and subject to collapse. Information relating to the position and activity status of the firefighter is therefore critical in helping the subject to navigate the environment and to enable safe extraction in the Non Line of Sight (NLOS) case [6]. This information is also valuable in search and rescue situations, to enable more optimal and efficient use of personnel on the ground.

B. SAFESENS Localisation Technologies

The SAFESENS project has developed a Personnel Safety Monitor, the purpose of which is to become a tool for first responders and their commanders to help with indoor navigation in obscured conditions in a fire situation, and to give an assessment of the safety of the first responder. For *indoor localisation*, a system is required that is independent of the existing building infrastructure, since this infrastructure may become unreliable or damaged in a fire situation. SAFESENS has integrated into the platform a hybrid inertial, positional and navigation module illustrated in Figure 3. The modules' onboard sensors are capable of providing information to enable activity to be classified and position to be determined in deployment scenarios where there is little supporting existing wireless infrastructure in place.

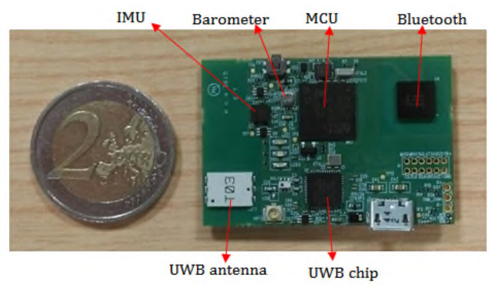

Figure 3. Hybrid Inertial, Positional and Navigation Module

The hybrid inertial, positional and navigation module is designed to be worn by each first responder attached to the straps of their Self-Contained Breathing Apparatus (SCBA). The hardware comprises inertial and magnetic sensors (accelerometer, gyro, and magnetometer), a barometer, a temperature and humidity sensor, an Ultra-Wide Band (UWB) ranging transceiver and a Bluetooth Low-Energy (BLE) transceiver. The module communicates sensor data to a smartphone carried by the firefighter employing BLE which in turn transmits data to a central server for processing. Ranging data is given by the UWB transceiver which measures the range between the worn module and the nearby anchors to track the firefighter [7]. Anchors can be stationary units deployed as part of the exercise or alternatively, other modules worn by accompanying firefighters. The firefighter's position and current activity is calculated on the central server as illustrated in the system architecture diagram in Figure 2.

IV. Vital Signs Monitoring

A. SAFESENS Vital Signs Monitoring

The integration of vital physiological measurements could help commanders to better predict the firefighter's or other first responder's health condition while performing critical tasks or in harsh environments. An important vital parameter is the heart rate which can be calculated and monitored from either Electrocardiography (ECG) or Photo Plethysmography (PPG) signals. Fabric-based, dry electrodes have been intensively investigated for wearable ECG measurements but still need complex algorithms to eliminate motion [8]. In the SAFESENS project, we are focusing on reflective PPG measurements based on optical sensors which are more precise in mobile conditions when the sensor is attached to the skin in an appropriate way [9]. The skin volume changes due to blood pressure variations and thus correlates to the heart rate. An algorithm first removes the impact of ambient light leakage and motion artefacts, and determines the pulse period. By measuring the PPG at multiple wavelengths, it is possible to detect changes in blood composition. For instance, the change from hæmoglobin (Hb) to oxygenated hæmoglobin (HbO_2) can be detected by a relative change in red and infrared absorption [10].

B. Integrating electronics into a firefighter glove

The SAFESENS firefighter glove demonstrator consists of a selected multi-chip package featuring 3 emitters (green, red, infrared) and one detector in a small package (4.7mm x 2.5mm x 0.9mm) enabling the measurement of the heart rate and pulse oximetry. The chip is integrated into an EN 659:2003 + A1:2008 certified, professional leather glove for the fire brigade and features the highest industrial cut resistance and fire blocking levels. The sensor position is designed to be placed in an unobtrusive body area: the base of the left hands' index finger (assuming right-handed fireman) allowing the user to touch objects without feeling the electronics. In order to contact the sensor and skin, a small hole was pierced into the glove. The controller unit is placed in a little pocket at the edge of the cuff at a distance of 250mm to the sensor.

Figure 4. SAFESENS Firefighter Glove Demonstrator: X-ray images of the Textile-integrated Stretchable Electronic System

A soft and expandable circuit board was developed to integrate the components into the glove. The Stretchable Circuit Board (SCB) consists of thermoplastic elastomers and copper conductor tracks in a meandering shape as 2-D spring elements. Thus, the SCB withstands bending and stretching making it a suitable technology for the integration of electronics into textiles. The components were assembled on the SCB by low-temperature soldering (SnBi) and under filled with an epoxy material for improved reliability against mechanical stress. The system was applied to a fire retardant nonwoven and finally laminated onto the inner textile layer of the glove [11][12][13], as shown in Figure 4.

C. Signal acquisition and processing

The sensor front-end is a single integrated circuit containing all necessary analog circuits to drive the LEDs and to determine the photocurrent from the photodiode, and a full-featured ARM M0+ microcontroller core to run the algorithms for the heart rate and the blood oxygenation calculations. A second IC contains the wireless transceiver to connect the sensor to a Personal Area Network. In the demonstrator, the sensor communicates over a Bluetooth Low Energy link, with a protocol fully compatible with the indoor localization module. The PPG sensor can either transmit continuous measurements or act on user-selectable alarm thresholds.

V. Flammable Gas Sensing

A. Introduction to Flammable Gas detection

In the process of a burning building, a flashover is a much feared stage. A flashover occurs at the moment when temperatures are so high that present flammable materials and gasses will spontaneously combust. Flammable gasses pose a particular risk during flashovers. Before a flashover, the high temperature results in partial decomposition and release of flammable gasses. When sufficient oxygen is present, or is introduced due to opening or breaking of doors and windows, spontaneous combustion will occur that will accelerate the propagation of fire and pose a severe safety threat to the fire fighters. To be aware of the flashover risks, it is advantageous to be able to detect the presence of flammable gasses.

B. SAFESENS technology developed for gas detection

In the SAFESENS project, it is envisioned that the first responders bring gas sensors to the scene that are integrated in their current equipment. The helmet was chosen as the most suitable location for the gas sensor, since it is a rigid structure that is in close contact with the surrounding atmosphere.

Hydrogen may be detected using a Pd-Ni alloy as a thin film deposited onto a silicon wafer substrate, which changes its electrical resistance in the presence of H_2, which can be electrically transduced.

Methane may be detected using an amperometric electrochemical sensor. In this type of electrochemical sensor, a chemical reaction takes place that involves electron transfer in the chemical reaction pathway. By leading these electrons through an external circuit an accurate current measurement can be performed, that is directly related to the amount of gas that is reacting. The amount of reacting gas is in its turn linearly related to the amount of gas in the surrounding atmosphere. In the SAFESENS project, a thin film methane sensor was developed, that uses an ionic liquid as the electrolyte. Previously, it was reported that such sensors can detect ethylene [14], and ammonia [15].

The hydrogen sensor is based on an alloy system described in [16]. Instead of using a van der Paw structure, a Wheatstone half-bridge was realized, which gives first order temperature compensation. The Pd-Ni film was deposited using a co-sputter process from pure Pd and Ni sputter targets. Film thickness was in the range of 100nm.

The methane sensor is based on the ammonia sensor that was previously described in [15]. In brief, a system of interdigitated platinum micro electrodes is made on a silicon substrate. The third electrode is a gold electrode that meanders between these interdigitated electrode, and serves as a pseudo reference electrode. On top of these electrodes, a thin film of an ionic liquid is deposited, to obtain an electrochemical cell sensitive to methane. The chosen ionic liquid is $[C_4mpy][NTf_2]$, as this system results in an electrochemical cell that is sensitive to methane [17].

VI. Occupancy Monitoring

A. *Introduction to Occupancy Monitoring Systems*

Occupancy estimation uses the readings from a sensor network to extract more contextual information of the building usage. It can enable the idea of smart building in different ways by: i) improving the comfort of the occupants by controlling lights, temperature, and humidity based on occupancy; ii) reducing energy costs by controlling lights and Heating, ventilation, and air conditioning (HVAC) equipment based on occupancy; iii) improving the convenience; iv) providing real-time occupancy in fire events. It can also offer technical advantages in a two-fold way: i) cost-benefit trade-off analysis for the selection of sensors and their placement; ii) complementary sensor measurements based on models of building usage.

B. *SAFESENS Technologies for Occupancy Detection*

The challenge of real-time occupancy estimation is to determine the number of people in different areas of a building over time. Under such operational settings, an estimation variance, along with a confidence level, should be provided within a short delay and fast update rate.

Due to the high deployment cost and large errors that people counting sensors suffer from, measuring occupancy throughout a building from sensors alone is not sufficiently accurate. Indeed, data collection from sensors is not perfect, and it is assumed that each sensor is subject to noise and environment clutter. Also, if sparsely deployed, the ability of sensors to detect occupancy change is limited by their coverage. In this way, occupancy estimation largely depends on the existing sensor technologies.

Occupancy estimation aims to adaptively correct noise and lack of observability errors by subdividing the approach into two sub-problems [18]:

i) *modelling*, investigates how to build a model to utilize prior knowledge and to simulate the occupants' movement behaviors in the building;

ii) *estimation*, defined as the process to obtain the hidden state of a system given a model and incomplete observational data.

In SAFESENS, the modelling follows the spatial topology of the floor, as in [19], where each graph node is considered a state. It can assume either an *occupancy state*, related to any zone of the building, or a *flow state*, which reflects the uncertainty in how people move from zone to zone. This modelling permits to divide the building into non-overlapping zones, defined by a hierarchy of different spatial scales, namely floor-level, zone-level and room-level.

For the estimation, a Kalman filter (KF) framework is adopted. Due to the non-linearity of the underlying data (pedestrian behavior) and the adopted linear modelling approach, we study the performance of linear and non-linear kalman estimators, such as Ensemble KF (EnKF), bank-of-filters-based (IMM, MMAE), among others.

VII. Results

A. *Data Visualisation on the Smart App*

To validate our system, and to do more real life experiments, we have installed a demo of the SAFESENS localisation platform at Tyndall near the canteen area. Under heavy NLOS and with limited available anchor nodes, the system can achieve 0.5m accuracy. Figure 5 shows the visualization front end for the SAFESENS system.

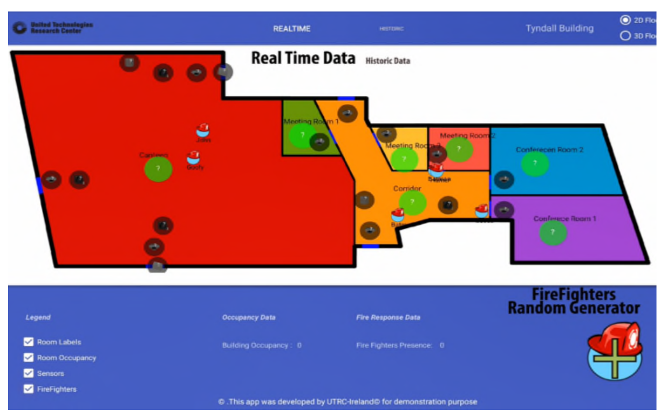

Figure 5. Occupancy and Firefighter Data Visualisation.

B. *Location Tracking and Activity Monitoring*

The positioning and tracking performance of the module has been evaluated. An additional calibration step was added to account for antenna delay and to improve ranging performance. The experiments comprise of an evaluation of the mobile performance employing a Least Square Estimation (LSE) algorithm. Results before and after calibration are illustrated in Figures 6 and 7, respectively. For each experiment, a reference path (shown in the figures below in blue) was determined for the mobile subject and

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communicated via markers on the floor. The tag was instrumented on the arm of the subject, who subsequently simulated the emergency responder walking along the reference path. The green path illustrates the calculated trajectory of the subject employing the module. The results indicate that the tolerances are acceptable for the prescribed application. Results for the activity classification machine learning algorithms are presented in [20].

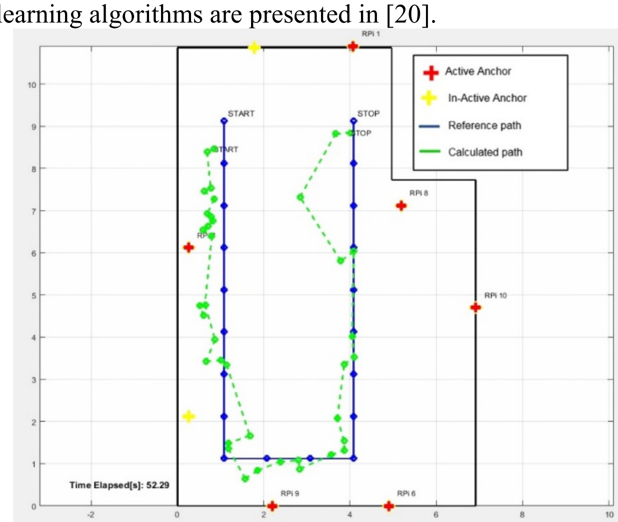

Figure 6. SAFESENS hybrid inertial, positional and navigation module mobile tracking performance prior to calibration

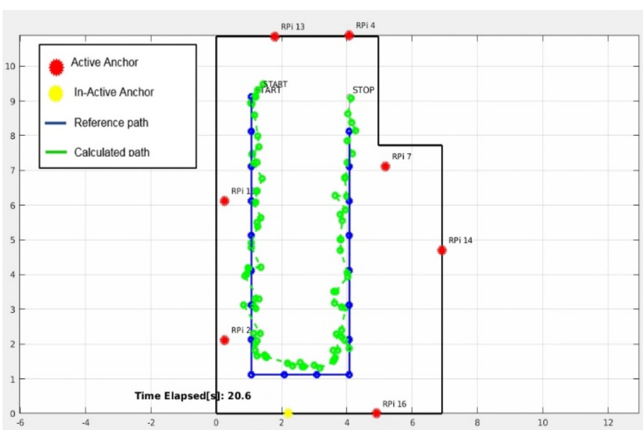

Figure 7. SAFESENS hybrid inertial, positional and navigation module mobile tracking performance following calibration

1) Vital Signs

The vital signs monitor is implemented as a finger ring embedded in the firefighter glove. It can operate in two different modes: high-resolution heart-rate, or combined heart-rate and blood oxygenation. The heart rate does not require multiple wavelengths, and thus a more optimal LED firing pattern can be selected to either lower the total power consumption or increase the sampling rate.

Estimation of the blood oxygenation requires alternate firing of red and infra-red (IR) Light Emitting Diodes (LEDs), and a more complex algorithm. An example of the captured data is shown in Figure 8.

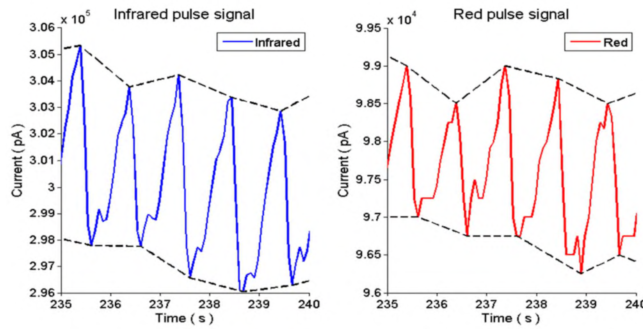

Figure 8. Captured infrared and red PPG signals.

The PEFAC algorithm [21] was selected for the heart rate detection. This method estimates the heart rate from the frequency spectrum. By expressing the frequency in the log-domain, the distance between the fundamental frequency and its harmonics doesn't depend on the absolute value of the fundamental frequency. By convolving the spectrum with a matched filter, the spectra of the harmonics are accumulated and noise is rejected. The oxygen saturation (SpO_2) is then derived from the ratio of ratios R, which is defined by equation 1:

$$R = \frac{(AC/DC)_1}{(AC/DC)_2} \quad (1)$$

Where AC and DC are the peak-to-peak amplitude and the baseline of the PPG pulse, respectively. These values are found by applying a min/max envelope tracker on the cleaned PPG signal. The following relationship between the ratio R and the SpO_2 is then used as in equation 2:

$$SpO_2 = \frac{\varepsilon_{d1} - R(l_2/l_1)\varepsilon_{d2}}{R\left(\frac{l_2}{l_1}\right)(\varepsilon_{o2} - \varepsilon_{d2}) + (\varepsilon_{d1} - \varepsilon_{o1})} \quad (2)$$

Where ε_o and ε_d are the extinction coefficients for HbO_2 and Hb. The constants l_1 and l_2 are the path-lengths for the two wavelengths and depend strongly on the scattering coefficient. For the two wavelengths, in the red and infrared regions which are used in the glove ring sensor (IR 950nm and red 660nm), l_1 and l_2 are expected to differ and they are unknown. SpO_2 can be derived from R through the calibration process by assuming that l_2/l_1 is a constant that is independent of inter-subject variability in the circulatory system. In this case, the coefficients are constants and can be determined through calibration. If the parameter l_2/l_1 changes between different subjects, in particular between the healthy subjects on whose fingers the calibration was performed and the fireman wearing the glove, inaccuracy in the SpO_2 measurement is to be expected. Relative changes for a single subject are accurate.

C. Flammable Gas Sensing

The hydrogen sensor was evaluated using humidified synthetic air with different amounts of H_2 added, in the range from 0.02% to 2% volume concentration. The gas was fed to the sensor with a nozzle with a flow of 1slm (standard liter per minute). The sensor chip was externally heated to temperatures of up to 140°C. It was found that 0.02% concentration already results in a detectable sensor signal. For concentrations above 0.5%, saturation of the signal began to be observed. Response time t_{90} was found to be in the range of 100s. Further reduction of response time is to be achieved by using Pulsed Laser Deposition (PLD) in order to generate a porous Pd-Ni layer, facilitating the H_2 transport into the layer.

The methane sensor was evaluated in a gas mixing chamber, where gas flows of methane were mixed with compressed dry air. Initial experiments consisted of cyclic voltammetry, where the voltage of the sensor is scanned to observe at which voltage the largest effect of methane exposure is observed. In Figure 9, the cyclic voltammogram of the sensor with and without 5% methane exposure is plotted. The difference between the current levels is plotted with the dotted line, and should be evaluated on the right Y-axis. The difference between the observed currents is small compared to the background current. To make the difference more visible, the currents with and without methane exposure were subtracted, and plotted. From these plots, it becomes clear that the largest current difference is observed between -0.5 and -1.5 V. The extreme voltages near -2 and +2 V are excluded, because water electrolysis will occur at these voltages when measurements are performed in humid air, which will interfere with the detection of methane.

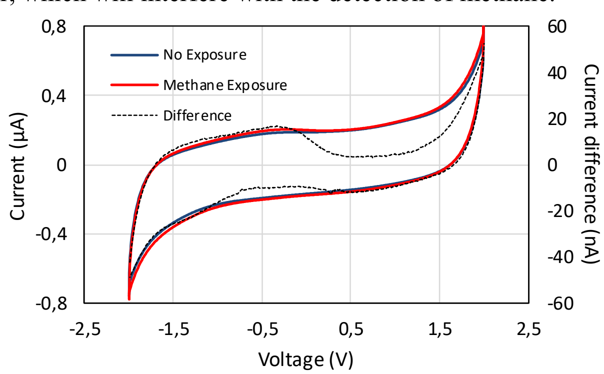

Figure 9. Cyclic voltammetry to determine most suitable voltage level for methane detection.

To determine the response of the sensor, the voltage was fixed, and the current was used as an indicator of the methane exposure. In Figure 10, the current that is resulting of 5% methane is given.

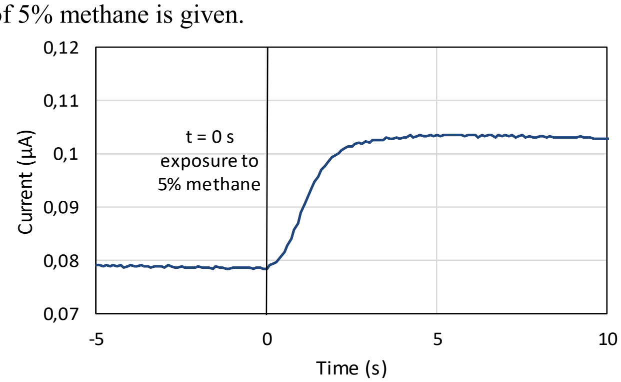

Figure 10. Current response to an exposure of 5% methane

This figure shows that the sensor has a fast response time, and that the gas level can already be detected within a few seconds, which is crucial for first responders.

D. *Occupancy Detection*

The deployment scenario is very particular since it depends on the physical venue, the sensor network characteristics and the application domain. Therefore, the solutions will perform very differently from scenario to scenario. For these reasons, the conducted experiments consider the combination of three characteristics: i) physical layout; ii) sensor topology; iii) data modelling (e.g., synthetic-random, synthetic- pedestrian; real sensors).

Due to lack of space, we here only present the results for some estimators and for one tested scenario, which consists of 6 rooms, with two different sensor topologies: TA) two camera sensors with oblique view towards ground-floor, situated in two rooms, and a camera sensor with top-down view, positioned between two rooms; TB) camera sensor in each room and the same top-down view camera between two rooms. The data was simulated using the Helbing social force model [22], rules for interactions between occupants and obstacle avoidance awareness. The simulation considers a total occupancy up to 6 people during 9000 samples (approximately lasting 7.5 minutes).

As expected, having a sensor in every zone dramatically improves the overall estimation. Considering all the experiments, we verified that the linear estimators are preferred for local measurements but they show degradation of performance through time, as well as for global estimation. An interesting conclusion is that a bank of linear filters solutions show competitive results, which might open further investigation issues regarding their extension to the combination of linear and non-linear estimators to balance local with global estimation. For more details, please refer to [23].

TABLE I. EVALUATION METRICS FOR EACH ESTIMATOR FOR T = 90000 SAMPLES

Estimator	Topology	MSE	Precision	Recall	F-measure
KF	TA	1.445	99.81	53.85	69.96
	TB	0.665	99.88	68.42	81.21
EnKF	TA	1.734	93.74	51.51	66.49
	TB	1.003	97.42	56.47	71.50
HF	TA	1.553	99.88	49.67	66.61
	TB	1.554	99.88	49.94	66.59
IF	TA	2.826	99.56	49.36	66.01
	TB	1.482	99.60	50.95	67.41
UKF	TA	1.373	99.37	54.76	70.61
	TB	0.657	99.88	68.44	81.22
IMM	TA	1.384	99.86	53.76	69.90
	TB	0.781	97.60	63.81	77.17
MMAE	TA	1.423	99.81	53.92	70.01
	TB	0.664	99.88	68.42	81.22

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VIII. CONCLUSIONS AND FUTURE WORK

The SAFESENS system is currently deployed in the Tyndall National Institute in Cork, Ireland where the integration activity focuses on the occupancy detection and firefighter activity tracking. The deployment activity continues to progress so as to integrate datasets from the other sensors integrated in the system, to improve accuracy of the sensor readings and develop robust communications mechanisms to augment the infrastructure based communications currently used in the demonstration activity which is Wi-Fi based. This will focus on UWB based Media Access Control (MAC), routing and scheduling protocols to maximize energy efficiency and minimize system latencies. The smart phone application is currently under development to integrate data sets from all sensors for upload to the data server for analytics and final demonstration.

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