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Sniffer, a protein-based advanced VOC sensor for victim search

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Abstract—a miniaturized gas-sensing module composed of both commercial off-the-shelf gas sensors along with a novel sensor array combining Quartz Crystal Microbalance transducers coated with Odorant Binding Proteins (OBP) was developed. The so-called “sniffer” module was integrated into a search and rescue robot with the ultimate goal of improving the efficiency of Urban Search and Rescue (USaR) operations on disaster sites, typically following the collapse of buildings. The selection of sensors combined with a fuzzy logic algorithm were aimed at localizing human victims, together with the support from other sensing technologies including both visible/infrared video cameras and a microphone, and at discriminating between both alive and deceased victims, in order to prioritize the USaR operations.

Keywords—victim search, gas sensor array, odor detection, embedded sensing module

I. INTRODUCTION

Global society will sadly face a severe increase of natural disasters in the future due to climate change. Therefore, strengthening societal resilience against disasters like flooding, forest fires or earthquakes has been declared a priority by many governments. In such events, the rescue of buried victims is a race against time as survivors in the hot-zone are often in immediate need for evacuation and medical treatment. According to statistics, uninjured survivors can survive up to around 72 hours when trapped in a collapsed building. As losing time in USaR operations may cost lives, it is therefore essential to quickly detect and localize trapped victims. However, there is very little information available on where victims might be located. As a result, USaR teams have to search the entire affected area for survivors [1]. In a typical collapsed building incident, it takes rescuers an average of five to eight hours to inspect one site and to obtain a full picture of the location of the victims required for a prioritization of their actions. While

canine units can detect a human scent, the foremost significant information that USaR teams need to obtain is where a victim is potentially trapped, the exact position under the rubble, and state of health. Traditional methods using endoscopes, infrared cameras, acoustic technology, bio radars and search dogs or simply calling out for trapped victims all have their limits [2]. Hence in the framework of the collaborative project “CURSOR”, funded by the European commission, and aiming to provide novel and highly innovative technologies for first responders to facilitate their operations, a miniaturized sensing module was developed to detect gases and vapours that may help to locate a victim. This “sniffer” module includes a combination of off-the-shelf gas sensors together with a dedicated “odor sensors” consisting of an array of QCM transducers coated with OBP-based sensitive coatings. Such sensing module was embedded into a small-miniaturized search robot (Soft Miniaturized Underground Robotic Finders called “SMURF”), also equipped with other types of sensors (e.g. visible and infrared cameras, microphone) in order to carry out victim search in rubble piles. The multivariate data produced by the “sniffer” are processed by a fuzzy logic algorithm in real time in order to detect the presence of human victims trapped under collapsed building, and to determine whether the victim is deceased or alive, based chemical emission from the victim. This article described the technological achievements associated with the development of such a sniffing module, and presents the first results obtained from field measurements.

II. DESCRIPTION OF THE SNIFFER MODULE

A. Off-the-shelf gas sensors

The sensing module was equipped with a Sensirion SCD30 carbon dioxide sensor where the principle of operation relies on infrared absorption by CO₂. The purpose of this sensor is to detect the presence of CO₂ in exhaled air from alive victims. Also included in the module is a metal oxide resistive Sensirion SGP30 Volatile Organic Compound (VOC) sensor, aiming to

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detect general VOC emission from victims, either alive or deceased. Finally a stand-alone Sensirion SHT3 temperature and humidity sensor was also integrated in order to monitor environmental parameters and eventually overcome issues related to the influence of those parameters on the gas sensor responses. The electrical interfaces of these sensors to the microcontroller are via an I2C protocol serial bus.

B. Dedicated odor sensor array

A dedicated biosensor array was also developed in order to detect the presence of small odorant molecules emitted from victims. The sensor array consists in four QCM transducers (resonant frequency 20 MHz) coated with Odorant Binding Proteins as sensitive coatings. Thus, it is relying on chemical interactions of the odorant target compounds with individual OBPs immobilized on each transducer along with gravimetric transduction. The immobilized OBPs were pigWTOBP1, AgamOBP1, AgamOBP1_S82P, and AgamOBP4. They were selected because they were already performing well in terms of sensitivity, selectivity and stability in a similar sensing configuration as reported elsewhere [3]. Expression of these proteins has been described in this latter paper. Another factor that was used to select these four proteins was the existence of their respective x-ray crystallography structures to allow to accurately model perhaps in the future potential mutant proteins that will be even more selective to our target volatile molecules.

Prior to this development, extensive literature search was carried out in order to identify relevant chemical markers that are indicative of the presence of either alive or deceased victims [4-6]. For live victims, a first criterion was to select markers that have void concentrations at least 10 times higher than the urban-air background. A second criterion used was if at least three of the emission sources Faeces, Urine, Breath, Skin, Milk, Blood, and Saliva emits the marker. By using the above criteria, seventeen potential markers were selected for the detection of entrapped live victim. Among those one can cite for instance acetone or n-heptanal. For the dead victims, four main potential markers were identified: cadaverine (pentane-1, 5-diamine), putrescine (butane-1, 4-diamine), skatole (3-methylindole) and indole. These four markers are believed to be key compounds that contribute towards the characteristic odors of decay. To demonstrate the binding capability of the selected markers to the binding pockets of the four proteins we have carried out molecular docking of some of those markers with the selected OBPs. (Fig. 1).

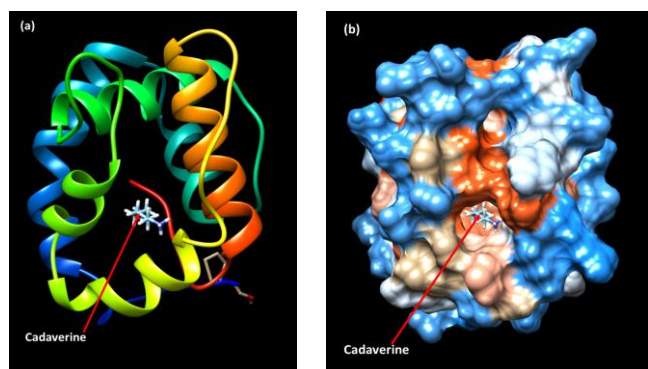


Fig. 1. Binding of cadaverine to the binding site of AgamOBP1. In (a) cartoon representation of the structures and (b) hydrophobicity surface representation

C. Sensing module read-out

Two microcontrollers are incorporated into the system – one is dedicated to reading information from the of-the-shelf sensors and for external communication with the robotic SMURF. The other is dedicated to reading the frequency data from the QCM biosensor array. The MAX32625 microcontrollers were chosen because they are very low power devices, and they incorporate five 32-bit counter/timers which is ideal for interfacing to quartz crystal microbalances with minimal external components. The microprocessors are connected to each other and communicate with each other using an RS232 serial interface. Each microprocessor has a USB port for communication to an external computer and this also serves as a programming interface. An L291 H-Bridge device provides a driver circuit for driving a small air pump (Thomas G 6/01-K-EB9L) at variable speed using pulse width modulation. Non-volatile memory was incorporated to store variables and settings and an FRAM device (CY15B104Q) was chosen. Components SCD30 and SCD31 were interfaced using the I2C bus. Power (5 Volts) was provided by a connector to the SMURF and data is transferred to the SMURF from the integrated module via an RS232 hardware interface.

To measure the frequency of a QCM sensor, based on its properties, the QCM system generally consists of i) an oscillator circuit (obtaining stable frequency signal of the QCM sensor, at the resonance frequency), ii) a frequency counter (measuring the frequency signal of the QCM sensor), iii) software (monitoring the frequency signal, processing, saving data, and controlling the QCM system). The requirements are stringent – typically an error of $< 0.001\%$ is required. We chose a solution requiring minimal external hardware electronic components. Here a reciprocal measurement approach was adopted. This is a class of counter that makes a period measurement on input signal. It uses two counters – one of which is a reference and the other from the QCM to be measured. Each quartz crystal in the array of sensors is incorporated into a circuit that forms an oscillator at the resonant frequency of the crystal. Each of these is connected to a logic buffer, which is gated by one of the digital outputs of the microcontroller whose output can be triggered ON/OFF at a user defined time interval. A high stability 20MHz oscillator is used as reference and this is also gated by the same circuit. The frequency counting is then largely by the microcontroller. As a result, when enabled, the parallel internal 32bit counters from the microcontroller start counting the signals from 5 channels (4 QCMS and the reference oscillator). After a user defined time (in this case 1 second) the logic gate is disabled, the counters stop and the 32bit registers in the microcontroller read, the data then being processed and recorded. Each number read from a QCM channel is divided by the count from the reference channel and multiplied by the resonance frequency of that reference oscillator to give the measured frequency at that point. Because the two microcontrollers communicate with each other, data is transferred, assembled into package with the components off-the-shelf data recorded at the same time, processed through a fuzzy classifier (incorporating fuzzy rules that fused data from all the different sensor types), and sent to

the SMURF which in turns logs data on to a remote server so that a user can see the interpreted data.

A dedicated gas flow cell was designed and 3D-printed using SLA resin. The air pump was directly fitted into the 3D printed cell, thus preventing the use of unnecessary tubing and facilitating miniaturization. The PCB was also fixed to the flow cell. The entire device dimensions were 10 x 3 x 2.5 cm³. A photograph of the sniffing module is shown in Fig.2.

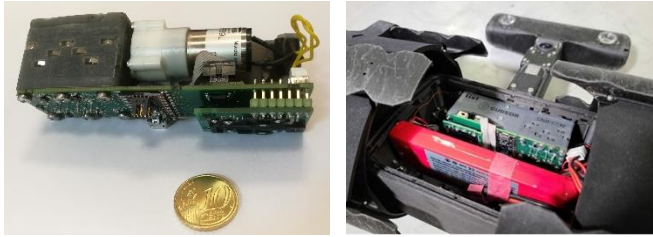


Fig. 2. Left: photograph of the sniffer sensing module, ; right: photograph of the module after integration into CURSOR's robotic SMURF

III. RESULTS FROM THE FIELD

After completing the integration of the gas sensing module into the miniaturized robot SMURF, trials were organized in the field in order to assess the performances of the device to locate victims and determine whether the victim is alive or deceased. In a first scenario, we used an apartment block being demolished in Aix-les-Bains, France, where the firefighters had already set fires for training purposes. For the trials we were allowed access to a basement area (Fig.3). Each room was approximately 2x3 m² large. The scenario consisted in hiding in one room either one volunteer in safe conditions, or a chemical mixture composed of 3-methylindole, putrescine and cadaverine soaked in tissue paper to simulate the presence of a deceased victim. Small robots with embedded sensing module were moved from the reference zone to the entrance of the room where chemical sources ("victims") were present. In this trial no previous data existed that would allow decisions to be made as to whether a live/deceased or animal scent was present – and all work had previously been done under lab conditions. Hence this field trial was used to assess the capability of the device to pick human scents in such environmental conditions, to assess the minimum distance from robot to victims for detection, and to collect data that would be used to refine fuzzy rules for the sniffer for later use.

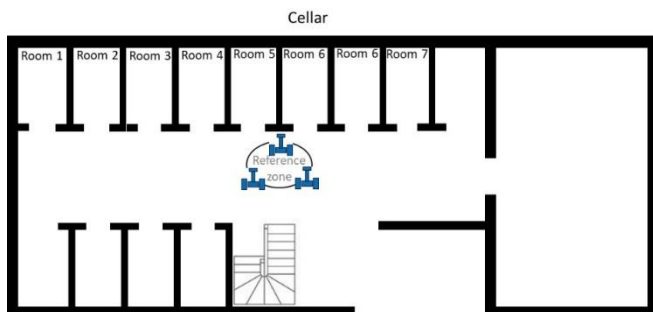


Fig. 3. Plan of basement area where victim search was carried out in the first scenario

Fig.4 shows typical raw responses from the different sets of sensors when a robot reached the entrance of a room containing either a living volunteer or markers of deceased victim. In the

presence of a living person in the room, a clear CO₂ signal is recorded as the robot enters the room. In contrast, in the case of the presence of chemical markers of deceased person in the room, residual CO₂ only is recorded from past experiments in the same room when living victims were present. The Sensirion SGP30 sensor shows a strong signal in the presence of a live volunteer in the room, and very weak signal otherwise. In contrast, the biosensor array seems to show stronger signals in the presence of deceased victims. This may be explained by the physical nature of the VOC emitted for both sources, the chemical markers of deceased victims featuring lower vapor pressure and higher molecular weights than VOCs emitted from a live person.

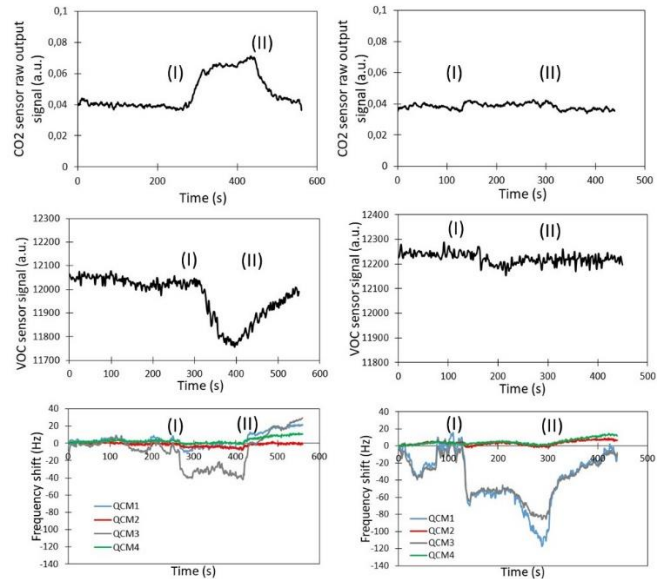


Fig. 4. Typical raw sensor responses from the sensing module. Left: in the presence of a live person in the room, right: in the presence of chemical markers of deceased person in the room. (I): the robot enters the room; (II): the robot leaves the room

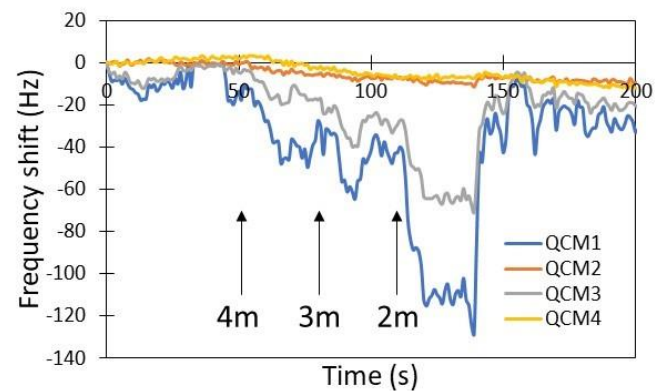


Fig. 5. Example of biosensor array response as the robot approaches a live victim hidden in a cellar room

Fig.5 shows an example of biosensor array response when a robot approaches a room when a live person is hidden. One can see here as in Fig.4 that each sensor in the array shows different sensitivity, as expected for the different molecular interactions between the emitted VOCs and the different OBPs immobilized on each QCM. In Fig.5, one can see that a significant signal is

observed, at least for two sensors, as soon as the robot reaches a distance of 4m away from the victim. A strong signal is observed when the robot stands at approx. 2 m away from the victim, which corresponds also to the time when the robot reaches the entrance of the room.

Following these trials and after taking into account the data gathered from the field, the victim detection fuzzy logic algorithm was implemented into one of the sensing module microcontroller and the output data from the algorithm, which constitutes a major data of interest for the first responders in operation, were also displayed successfully in real time on a dedicated general user interface (GUI). The upgraded robots were taken to a new field trial in a military training camp in Brignoles, France, where victim search was carried out in a large rubble pile. Many trials were carried out to determine the presence of a live victim (volunteer hiding in the rubble pile in safe conditions) or deceased victims (mixture of chemical markers of the presence of decaying body, as used during the previous trials, placed also in the rubble pile in strategic positions). The robots were found to be very effective for identifying the presence of live victims. Usually, a victim was detected when a SMURF equipped with the chemical sensing module was approx. 2-3 m from the victim, as shown by a high probability value of alive victim appearing on the GUI followed by alarm when passing the set threshold, after typically a few minutes of search around the victim area.

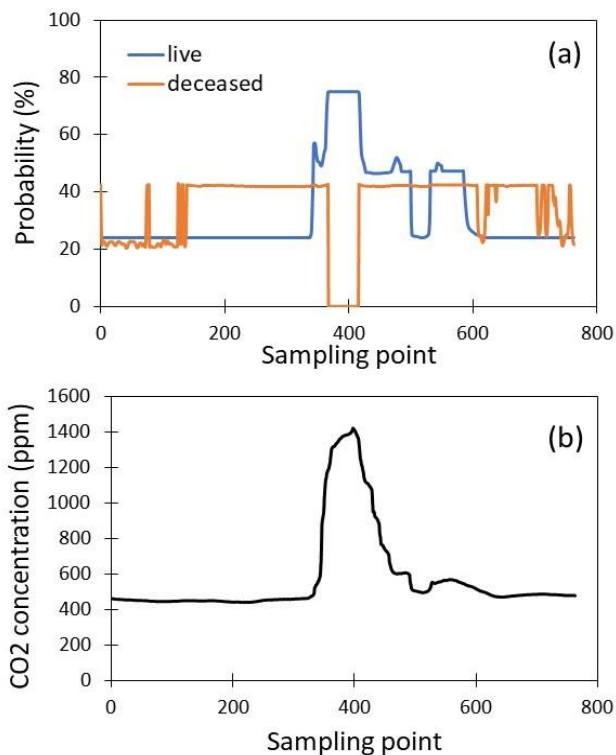


Fig. 6. (a) Example of real-time trace of probability of detection of live victim. The trace shows clear detection of the live victim around sampling point 400. Sampling was at approximately 4 second intervals, (b) CO₂ signal recorded simultaneously during this search.

Fig. 6(a) shows an example of real-time trace of probability of detection of live victim during search in a rubble pile. Fig. 6(b)

shows the corresponding CO₂ level recorded during the same search. As the robot approaches the victim, a clear rise in CO₂ level is observed, up to 1400 ppm, as expected from the breathing volunteer. When the robot reaches approx. 2m away from the victim, the probability percentage of finding a deceased victims drops from 40% to 0%, while the probability to find a live victim increases from 22% to 78%, this successful identification of a live victim under the rubble pile. Similar results were obtained for deceased victims while searching for tissue paper soaked with chemical markers and hidden under the rubble pile.

IV. CONCLUSION

A miniaturized gas sensing module (“sniffer”) comprising a combination of commercial gas sensors (VOCs, CO₂) together with state-of-the-art sensors based on olfactory proteins was, to our knowledge, developed for the first time for USaR operations and successfully tested. They are highly capable of detecting live persons from 2-3 metres away. We have also demonstrated the feasibility of successful integration of a the miniaturized sniffer into a robotic device (SMURF) to bring a new volatile chemical sensing tool that can augment imaging or auditory sensing capabilities in the robot in a reliable way. The robots equipped with sniffers were robust to physical shock after being dropped from drones and they were not affected by high temperatures encountered on site. These results give promise that this new tool could be a helpful addition to a SaR toolkit.

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