Expected Performance of a Mobile e-nose platform for Real Time Victim Localization

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Abstract. In this paper it is presented an analysis for the performance of the sensors of a mobile e-nose system that measures the atmospheric air, gas components’ concentrations (actually CO$_2$ and O$_2$), into a rubble void, where humans are entrapped, after a disastrous event that caused the collapsing of a building/construction. In this case, the entrapped humans in the void, they affect the air composition and temperature into the void. The existence of human(s) creates CO$_2$ source(s), O$_2$ sink(s), and heat source(s) as well (from body temperature). The existence of the entrapped humans constantly affect the air composition and temperature into the void and makes gas components’ concentrations dynamic. There will be presented the human CO$_2$ source(s), and O$_2$ sink(s) inside a cavity. The final goal is to estimate the concentrations of CO$_2$ and O$_2$ into the cavity as a function of time, having as parameters the number of entrapped humans. Estimating the concentrations it will enable the operator of a mobile e-nose system with sensors of a specific sensitivity and specificity, to determine the possibilities of detecting the presence of humans in a rubble void, nevertheless without considering the effect of weather conditions.

1. Introduction

Urban Search and Rescue (USaR), operations, take place after a disaster that involves partial or complete collapse of an urban structure and results in the entrapment of people-victims. The cause can be a natural disaster such as an earth quake, explosion because of equipment failure, or a terrorist action. The victims are trapped in poorly ventilated confined spaces with limited or no space to move around. A number of technologies are being used to assist, complement, or even replace the trained search and rescue dogs [1]. An e-nose system is based on surrounding air sampling and the measurement of its composition for specific gases, indicating human presence. Such an e-nose system is specifically targeted for use in confined and narrow spaces where the detecting conditions are more favourable. It takes advantage of the small air refreshing rate in the confined spaces of the rubble that allows for the existence of large variations of the air composition when a human is present in a survival space-void. Specifically, CO$_2$ concentration it is approximately 400ppm in the atmosphere and 46.000ppm in the exhaled human breath. Concerning O$_2$, atmospheric air has 20.946% and exhaled breath 16%. Thus at a collapsed site's cavity, when humans are trapped inside, it is expected to affect the levels of the CO$_2$ and O$_2$ concentrations since they could be considered as sources of CO$_2$ and sinks of O$_2$, thus changing the composition of the air inside the void. The number of victims in a cavity and their weight, as well as their metabolic state, they define the CO$_2$ supply rate in the cavity (source), and also the O$_2$ absorption rate (sink). Additionally the entire cavity where a victim is entrapped, it is not sealed. In the general case

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it is expected to be ventilated, allowing the escape of target particles (CO$_2$ and O$_2$), and the renewal of the gas mixture inside the void with fresh atmospheric air. The ventilation of a cavity, with air sources outside (could be fresh air, or, air from an adjacent cavity), is influenced by the openings of the cavity. A human detection e-nose system to be efficient in rescue operations, proper estimation of the concentrations of the target gases/substances to be detected in a specific cavity, it is crucial. Various sensor technologies have different limits of detection (noise floor of the sensors). The differentiation of the concentrations of CO$_2$ and O$_2$ inside the void, in comparison with those in fresh atmospheric air, should be above the e-nose sensors’ noise floors, so to be feasible to reveal information about the presence of victims inside a cavity under investigation. Section 2 of the paper formulates the problems that have to be solved and section 3 estimates the anticipated concentration of CO$_2$ and O$_2$ into a void/cavity as a function of time (in the rest of the paper the terms void and cavity are used as equivalent). Section 4 examines the anticipated performance of an e-nose system considering various cases of entrapped humans in a void, the characteristics of the CO$_2$ and O$_2$ sensors and their noise floor detection limits. Section 5 concludes the paper.

2. Formulation of the problems to solve
In this section we discuss how to formulate the problem and get the individual mathematical representation to solve. The entire void is considered as a confined space of constant volume $V_c$. Entrapped humans, will be considered as sources of exhaled air and sinks of cavity’s air at the same time. Taking into account those sources and sinks of air of the void, and assuming that the movement of air molecules inside of it creates a uniform distribution, then the mean concentrations of CO$_2$ and O$_2$ inside the void, could be estimated. Assuming that all air inside the void is mixed perfectly within the entire volume of it and that all particles have a uniform distribution, it is sufficient to estimate theoretically the concentration mean values for CO$_2$ and O$_2$ inside the void and then by comparing them with the sensors’ noise floor, to decide about investigating further a cavity. The sampled and measured air (near the air entrance of the e-nose system), could be assumed that represents all the air in the cavity under investigation and the differentiation of the concentrations of CO$_2$ and O$_2$ inside the void, has to be higher than the e-nose system’s detection limits, so to be detectable.

3. Estimation of mean concentrations in a cavity as a function of time
There had to be studied CO$_2$ and O$_2$ sources and sinks to estimate the mean concentrations as a function of time. Concerning the initial conditions of the problem, after the collapsing of a building because of an abrupt catastrophic event, the composition of the atmospheric air inside the created voids/cavities in the rubble, it is assumed to be near the same composition as that of the atmospheric air out of the cavities (400ppm for CO$_2$ and 20,946% for O$_2$). In case, that there will be entrapped humans in the void, then its air composition will be affected. The problem is to estimate how these factors are combined and how they affect CO$_2$ and O$_2$ mean concentrations in the void, as a function of time.

3.1. Mean Concentrations Equations
The mean concentration $C_x$ of CO$_2$ or O$_2$ ($C_{CO_2}$ or $C_{O_2}$ respectively), inside a room or a cavity of volume $V_c$, is given by the expression $C_x = \frac{\text{number of molecules of the specific gas } x \text{ component in the cavity}}{\text{total number of air molecules in the cavity}}$ (ppm). Since cavity’s volume $V_c$, remains unchanged, also the total number of air molecules in the cavity for a specific temperature could be considered unchanged. In a cavity that has a number of openings for entering fresh atmospheric air, and with entrapped humans, assuming that before the entrapment of the humans the space was filled with fresh atmospheric air, the following parameters would influence the number of molecules of CO$_2$ or O$_2$ in the cavity:

- The concentration $C_{xf}$ of this specific gas component in the fresh atmospheric air and the concentration $C_{xe}$ in human’s exhaled breath, along with the fresh air flow rate (lit/min) into the room/cavity $F_f$ and the exhaled breath flow rate $F_e$. 

The concentration $C_{xc}$ of this specific gas component in the air going out from the openings of the room/cavity and its outgoing flow rate (lit/min) $F_c$.

The concentration $C_{xc}$ of this specific gas component in cavity’s air, inhaled by the entrapped persons in the room/cavity (outgoing from the cavity to humans’ lungs), flow rate (lit/min) $F_i$. Temperature difference between $T_c$ and $T_i$, (temperature inside the room/cavity $T_c$ and outside $T_i$), might increase or decrease the temperature into the cavity from $T_c$ to $T_i$ and change the total number of air molecules in the cavity. Nevertheless this change doesn’t affect the concentration of any of the air components as far as the concentration expression refers to volume ratio (air component partial volume), or mole fraction/ratio (ppm or %). According to gas laws the proportionalities among air components molecules and thus partial volumes will remain the same.

Assuming that when fresh air enters the void its temperature in very short time becomes the same as the temperature inside the void, the principle used to estimate mean concentration of CO$_2$ or O$_2$ inside the cavity, is that cavity’s volume and pressure, remain unchanged and thus airflows coming into the cavity must be balanced with the exhaust flows. Airflows are considered for a specific opening (humans are handled as openings), as positive when they enter into the cavity and negative when they are going out of it.

Then $\sum F = 0 \Rightarrow F_f + F_e - F_o - F_i = 0$. Additionally because the inhaled and exhaled air flow rates are the same ($F_e = F_i$), it results that $F_f = F_c$. The change of the partial volume of an air component $x$ in the cavity, within a very small fraction of time $dt$, it would be:

$$\Delta V_x = (F_f \cdot C_{xf} + F_e \cdot C_{xe} - F_c \cdot C_{xc} - F_i \cdot C_{xc}) \cdot dt$$

Also the concentration change is given by:

$$dC_{xc} = \frac{\Delta V_x}{V_c} = \left(\frac{F_f \cdot C_{xf} + F_e \cdot C_{xe} - (F_c + F_i) \cdot C_{xc}}{V_c}\right) \cdot dt \Rightarrow$$

$$\frac{dC_{xc}}{dt} = \frac{F_f \cdot C_{xf} + F_e \cdot C_{xe} - (F_c + F_i) \cdot C_{xc}}{V_c} = \frac{F_f \cdot C_{xf} + F_e \cdot C_{xe}}{V_c}$$

The solution of the above differential equation is as follows:

$$C_{xc}(t) = K + K_0 e^{-\frac{F_f + F_e}{V_c} t}$$

Substituting the solution into the differential equation we get:

$$\left(\frac{K + K_0 e^{-\frac{F_f + F_e}{V_c} t}}{V_c}\right) = \frac{F_f + F_e}{V_c} \left(\frac{K + K_0 e^{-\frac{F_f + F_e}{V_c} t}}{V_c}\right) = \frac{F_f \cdot C_{xf} + F_e \cdot C_{xe}}{V_c}$$

$$\Rightarrow K \cdot \frac{F_f + F_e}{V_c} = \frac{F_e \cdot C_{xe} + F_f \cdot C_{xf}}{V_c} \Rightarrow$$

$$K = \frac{F_f \cdot C_{xf} + F_e \cdot C_{xe}}{F_f + F_e}$$

Taking into account the initial conditions at time $t=0$ (when happened the catastrophic event) and $C_{xf} = C_{xc}(0) = C_{xf}$, $K_0$ is calculated as follows:

$$C_{xc}(0) = K_0 + K \Rightarrow K_0 = C_{xc}(0) - \frac{F_f \cdot C_{xf} + F_e \cdot C_{xe}}{F_f + F_e} \Rightarrow$$

The mean concentration of CO$_2$ or O$_2$ in the cavity, as a function of time, is given by the formula below:

$$C_{xc}(t) = \frac{F_f \cdot C_{xf} + F_e \cdot C_{xe}}{F_f + F_e} + \left(\frac{C_{xf} - \frac{F_f \cdot C_{xf} + F_e \cdot C_{xe}}{F_f + F_e}}{F_f + F_e} \right) e^{-\frac{F_f + F_e}{V_c} t}$$

Defining as $\frac{F_f}{F_e} = n_{Ff:e}$, then,
\[
\frac{F_f}{n_{F_f} e^{F_e}} \Rightarrow C_{xc}(t) = \frac{n_{F_f} F_e + C_{xf} + F_e \left( C_{xe} - n_{F_f} F_e + C_{xe} \right)}{n_{F_f} + 1} + \left( C_{xf} - n_{F_f} F_e + C_{xe} \right) e^{-\frac{n_{F_f} F_e + C_{xe}}{V_c} t}
\]

Also defining as \( \frac{C_{xf}}{C_{xe}} = n_{C_{xf} e^{C_{xe}}} \), then,
\[
C_{xc}(t) = \frac{n_{F_f} F_e + n_{C_{xf} e^{C_{xe}}} + C_{xe} + C_{xe} \left( \frac{n_{C_{xf} e^{C_{xe}}} - n_{F_f} F_e + C_{xe}}{n_{F_f} + 1} \right)}{n_{F_f} + 1} + \left( \frac{n_{C_{xf} e^{C_{xe}}}}{n_{F_f} + 1} \right) e^{-\frac{n_{F_f} F_e + C_{xe}}{V_c} t}
\]

Verifying the above formula of \( C_{xc}(t) \), we get \( C_{xc}(0) = C_{xf} \), as expected and that for \( t \to \infty \), \( C_{xc} \) converges, \( C_{xc} \to C_{xe} \left( \frac{n_{F_f} n_{C_{xf} e^{C_{xe}}} + 1}{n_{F_f} + 1} \right) \).

4. Air sources and sinks inside a rubble cavity and anticipated performance of the e-nose system.

Exhaled air from the entrapped human(s), contains increased concentration of CO\(_2\) (as part of human metabolic process), in comparison with the CO\(_2\) of the fresh atmospheric air outside the rubble. Specifically exhaled air composition, according to literature, \([1-4] C_{(CO_2)e} = 40.000 - 53.000 ppm\). Fluctuations are also significant depending on the person’s characteristics and physical condition \([2]\). The dry air of normal atmospheric air, contains roughly \( C_{(CO_2)f} = 405 - 420 ppm \) CO\(_2\), \([4]\). It is meaningless to use higher accuracy concentrations measurements since the fluctuations in a period of few days or in different near-by places might be significant \([4]\), and also increasing every year.

Concerning O\(_2\), exhaled air contains decreased concentration levels in comparison to the O\(_2\) in the fresh atmospheric air. Exhaled air contains \( C_{(O_2)e} \approx 13.6\% - 16.0\% \) \([2, 3, 5]\), and dry air of normal atmospheric air, contains roughly \( C_{(O_2)f} \approx 20,536\% - 20,946\% \), \([4, 6]\). Also for oxygen it is meaningless to use higher accuracy concentrations measurements since there are fluctuations as well \([4]\). Comparing the concentrations of exhaled and fresh air for CO\(_2\) and O\(_2\), we get respectively, \( \frac{C_{(CO_2)f}}{C_{(CO_2)e}} \approx n_{C_{(CO_2)e}} 0.008 - 0.011 \), and \( \frac{C_{(O_2)f}}{C_{(O_2)e}} \approx n_{C_{(O_2)e}} 1.2835 - 1.5401 \).

Concerning the exhaled air flow rate, for each victim depends actually on their weight. There have to be defined the number of breaths for a specific time period and also the volume of the average breath of a person, to estimate the exhaled air flow rate. The flow rate of exhaled air \( F_e \) in litres per minute, results as:

\[
F_e \text{ (litres/minute)} = \text{number of breaths (# breaths/minute) } \times \text{ tidal volume (litres)}.
\]

Specifically for the respiratory rate, for adults is usually 12-20 breaths per minute \([7, 8]\). Elderly people may have a slower breathing rate (10-18 breaths per minute) \([8]\). Children have a faster breathing frequency reaching up to 25-40 breaths per minute for infants \([9]\), as shown in Table 1.

About the volume of the average breath (tidal volume), of an adult or elderly person, it is estimated between, approximately 390 (women) and 500ml (men) \([10]\). Infants’ and children’s tidal volume is between 0.1 and 0.2 litres (Table 1). However, in absolute terms, the amount of air a person needs is determined by the mass of the person. On average a person requires 7ml/kg of body mass \([10]\). So an average male adult weighting 75kg would have a tidal volume of 0.525lt and as such an exhaled air flow rate of \( F_e = 6.3 - 10.5 lt/\text{min} \). Below in Table 1, are calculated the exhaled air flow rates for individuals at different ages \([11-13]\).

Table 1 gives a range for the flow rate of exhaled air \( F_e \), in litres per minute, from \( F_e = 20 \text{ breaths/min } \times 0.1lt/\text{breath } = 2.0lt/\text{min} \), (in case of a 3 years old baby), up to \( F_e = \)
20 breaths/min * 0.525lt/breath = 10.5lt/min, (in case of an adult male), which can be used to estimate the ratio \( F_f \), which can be used to estimate the ratio \( F_f = n \cdot F_e \).

**Table 1**: Exhaled air flows for individuals at different ages.

| description of individual                        | average weight (kg) | average number breaths / min | tidal volume (lt) | average \( F_e \) (lt/min) |
|-------------------------------------------------|---------------------|-------------------------------|-------------------|-----------------------------|
| adult male (35yo, 25% percentile)               | 75                  | 12-20                         | 0.5               | 6.3-10.5                    |
| adult female (35yo, 25% percentile)             | 57                  | 12-20                         | 0.4               | 4.7-7.8                     |
| children (10 years old)                         | 33                  | 15-20                         | 0.2               | 3.0-4.0                     |
| baby (3 years old)                              | 14                  | 20-30                         | 0.1               | 2.0-3.0                     |
| baby (6 months old)                             | 7.5                 | 25-40                         | 0.1               | 2.5-4.0                     |
| elderly male (>80yo, 25% percentile)            | 72                  | 10-18                         | 0.5               | 5.3-9.5                     |
| elderly female (>80yo, 25 percent.)             | 52                  | 10-18                         | 0.4               | 3.9-7.0                     |

Inspiration’s flow rate is considered the same as exhalation \( F_e = F_i \), and the concentration of the cavity’s inhaled air in \( CO_2 \) or \( O_2 \) is denoted as \( C_{(CO_2)e} \) and \( C_{(O_2)e} \), respectively.

**4.1. Mean Concentrations and sensor measurements noise floor**

E-nose systems usually use both, high speed and lower speed sensors. High speed sensors, like non-dispersive infrared absorption sensors, they ensure a fast detection method, but they have low accuracy (~5%). Sensors using less rapid technologies, like fluorescent light, they have higher precision (~2.7%), but their response is really slow [14]. Fast sensors are more preferable for e-nose systems targeted to USaR operations. The main reason is because they deliver data fast enough (up to a 2 Hz), to detect a point of interest during rubble searches. On average this is adequate to detect a change in concentration between 2 adjacent points in a cavity (about 1cm distance for a robotic platform with typical speed 3cm/sec). Nevertheless the accuracy of 5% on top of the picked-up noise, can further distort the signal and rise it up to 15%. There are alternatives adopted by such systems [14], and by using concurrently higher precision but slower sensors to complement the weakness of the low accuracy of the high speed sensors. In an attempt to evaluate \( CO_2 \) and \( O_2 \) sensors in an e-nose system for [15], the noise picked up for both categories of sensors has been measured and showed that \( CO_2 \) was in the range of 380-420ppm (average 406ppm), and \( O_2 \) percentage ranges were between 20.67%– 20.8% (average=20.72%). Measurements of sensors’ performance showed that particularly \( CO_2 \) sensor picks up a lot of noise. The \( O_2 \) sensor, on the other hand, is much more accurate and due to the nature of its detection method, provides a much smoother result. In order for an e-nose system used for USaR operations to detect victims with enough certainty and without creating false alarms to the rescue teams, the raw value acquired from the sensors should be at least two standard deviations away from the mean values of the fresh air outside the rubble. Using the values of standard deviation estimated for the e-nose system in [15], the “alarm” \( CO_2 \) concentration should be when \( C_{(CO_2)e} = 1.10798 \cdot C_{(CO_2)f} \). Similarly the “alarm” \( O_2 \) concentration should be if \( C_{(O_2)e} = 0.9995 \cdot C_{(O_2)f} \). These threshold values are the worst case scenario. If more than one measurements from the e-nose system are used for the decision making, particularly with filtering/averaging performed on a window of values, the limits of detection can be significantly reduced. The costs are response time and consequently in search/scanning speed.

**4.2. Mean Concentrations in equilibrium and human detection limits**

In section 3.1, it was shown that for \( t \to \infty \) the concentration of \( CO_2 \) or \( O_2 \) in a cavity/void \( C_{xc} \) converges to, \( C_{xc} = C_{xe} \cdot \left( \frac{n \cdot F_{fe} \cdot n \cdot C_{fe} + 1}{n \cdot F_{fe} + 1} \right) \).
In section 4, was shown that, \( \frac{c_{(CO_2)}f}{c_{(CO_2)e}} \approx n_{C_{(CO_2)}} \approx 0.008 - 0.011 \), and \( \frac{c_{(O_2)}f}{c_{(O_2)e}} \approx n_{C_{(O_2)}} \approx 1.2835 - 1.5401 \). Also it was shown that \( F_e \) ranges from \( F_e = 2.0 \text{lt/min} \), up to \( F_e = 10.5 \text{lt/min} \), which results that the ratio \( \frac{F_f}{F_e} = n_{F_f} \). Finally in section 4.1, was found that “alarm” \( CO_2 \) and \( O_2 \) concentrations are \( C_{(CO_2)e} \geq 1.10798 \ast C_{(CO_2)f} \) and \( C_{(O_2)e} \leq 0.9995 \ast C_{(O_2)f} \).

Thus clarifying further the “alarm” point for \( CO_2 \) it results the following inequality :

\[ C_{(CO_2)e} \geq 1.3346 \ast C_{(CO_2)f} \Rightarrow C_{(CO_2)e} \ast \left( \frac{n_{F_f} \ast n_{C_{(CO_2)f} + 1}}{n_{F_f} + 1} \right) \geq 1.10798 \ast C_{(CO_2)f} \Rightarrow \]

\[ \frac{n_{F_f} \ast n_{C_{(CO_2)f} + 1}}{n_{F_f} + 1} \geq 1.10798 \ast n_{C_{(CO_2)fe}} \Rightarrow \]

\[ \frac{n_{F_f} + 1}{n_{F_f} + 1} \ast \left( \frac{n_{F_f} \ast n_{C_{(CO_2)f} + 1}}{n_{F_f} + 1} \right) \geq 1.10798 \]

Considering the most difficult case where the concentration of \( CO_2 \) in the exhaled breath is minimum \( (C_{(CO_2)e} \approx 40.000 \text{ppm}) \), and in fresh air maximum \( (C_{(CO_2)f} = 420 \text{ ppm}) \), thus \( n_{C_{(CO_2)fe}} \approx 0.011 \), then the “alarm” point for \( CO_2 \) becomes :

\[ n_{F_f} \ast 0.011 + 1 \geq 0.01219 \ast (n_{F_f} + 1) \Rightarrow 0.9878 \geq n_{F_f} \ast 0.00119 \Rightarrow n_{F_f} \leq 830.08 \]

This finding shows that in case that the flow rate of the fresh air \( F \), is \( F \geq n_{F_f} \ast F_e = 830.06 \ast F_e \), then the \( CO_2 \) sensor of the e-nose system will not be able to detect a victim. Specifically for a child 3 years old alone in a void if \( F_f \geq 2m^3/min \) it will not be detected, and for an adult male also alone in a void if \( F_f \geq 7m^3/min \).

Similarly, clarifying further the “alarm” point for \( O_2 \):

\[ C_{(O_2)e} \leq 0.9995 \ast C_{(O_2)f} \Rightarrow C_{(O_2)e} \ast \left( \frac{n_{F_f} \ast n_{C_{(O_2)f} + 1}}{n_{F_f} + 1} \right) \leq 0.9995 \ast C_{(O_2)f} \Rightarrow \]

\[ \frac{n_{F_f} \ast n_{C_{(O_2)f} + 1}}{n_{F_f} + 1} \leq 0.9995 \ast n_{C_{(O_2)fe}} \Rightarrow \]

\[ \frac{n_{F_f} + 1}{n_{F_f} + 1} \ast \left( \frac{n_{F_f} \ast n_{C_{(O_2)f} + 1}}{n_{F_f} + 1} \right) \leq 0.9995 \]

For \( O_2 \), the most difficult case is when the concentration in the exhaled breath is maximum \( (C_{(O_2)e} \approx 16\%) \), and maximum as well in fresh air \( (C_{(O_2)f} = 20.946\%) \), thus \( n_{C_{(O_2)fe}} \approx 1,309125 \), and the “alarm” point for \( O_2 \) becomes :

\[ n_{F_f} \ast 1,309125 + 1 \leq 1,30847 \ast (n_{F_f} + 1) \Rightarrow n_{F_f} \ast 0.0006545 \leq 0.30847 \Rightarrow n_{F_f} \leq 471.26 \]

Analyzing this finding as well it is shown that in case that the flow rate of the fresh air \( F \), is \( F \geq n_{F_f} \ast F_e = 471.26 \ast F_e \), \( O_2 \) sensor will not be able to detect a victim. Specifically for a child 3 years old alone in a void if \( F_f \geq 1,2m^3/min \) it will not be detected, and for an adult male also alone in a void if \( F_f \geq 4m^3/min \).

Assuming that rescue teams need to evaluate about the probability of detecting humans in a cavity, under certain conditions (cavity openings and estimated fresh air flow rate), then by using the “alarm” points estimated above, it is possible to define the “resolution” of the e-nose system, i.e. the minimum number of humans that the system would detect under those specific conditions. Nevertheless further details for weather conditions should be known and taken into account and finally decide about the worthiness to investigate a void.
4.3. Mean Concentrations and time needed for equilibrium

In section 3.1, it was shown that the concentration of CO₂ or O₂ in a cavity/void $C_{xc}$ is given by the formula:

$$C_{xc}(t) = C_{xe} \times \left( \frac{n \cdot F_{fe} \cdot n \cdot C_{xe} + 1}{n \cdot F_{fe} + 1} + \frac{n \cdot C_{xe} \cdot F_{fe} + 1}{n \cdot F_{fe} + 1} \right) e^{-F_{fe} \cdot \frac{n \cdot F_{fe} + 1}{v_{c}} \cdot t}$$

From the above formula it is evident that when $t \to \infty$ the term $e^{-F_{fe} \cdot \frac{n \cdot F_{fe} + 1}{v_{c}} \cdot t} \to 0$.

A reasonable approximation for $t \to \infty$, is $F_{fe} \cdot \frac{n \cdot F_{fe} + 1}{v_{c}} \cdot t \approx 5$ and $e^{-F_{fe} \cdot \frac{n \cdot F_{fe} + 1}{v_{c}} \cdot t} \approx 0.0067$, small enough to be ignored.

Consequently when $t \approx 5 \cdot \frac{v_{c}}{(n \cdot F_{fe} + 1) \cdot F_{fe}}$, rescue teams may consider that equilibrium is reached and e-nose may be used to detect entrapped humans.

By using the estimations of section 4.2, in Table 2, there is presented the time needed at 3 different sized cavities, 52.5m³ (up to 15 victims), 26.5m³ (up to 5 victims) and 10m³ (up to 2 victims).

| Description of an entrapped human | Average $F_e$ (lt/min) | Cavity/Void size m³ | Average time (minutes) needed for detection by CO₂ sensor ($n \cdot F_{fe} \leq 830.08$) | Average time (minutes) needed for detection by both sensors CO₂ & O₂ ($n \cdot F_{fe} \leq 471.26$) |
|----------------------------------|------------------------|---------------------|-------------------------------------------------|-------------------------------------------------|
| adult male                       | 6.3-10.5               | 52.5                | 41                                              | 71                                              |
| elderly female                   | 3.9-7.0                |                     | 64                                              | 111                                             |
| children                         | 3.0-4.0                |                     | 93                                              | 163                                             |
| child (3 years old)              | 2.0-3.0                |                     | 132                                             | 232                                             |
| adult male                       | 6.3-10.5               | 26.5                | 21                                              | 36                                              |
| elderly female                   | 3.9-7.0                |                     | 32                                              | 57                                              |
| children                         | 3.0-4.0                |                     | 47                                              | 82                                              |
| child (3 years old)              | 2.0-3.0                |                     | 67                                              | 117                                             |
| adult male                       | 6.3-10.5               | 10                  | 8                                               | 14                                              |
| elderly female                   | 3.9-7.0                |                     | 13                                              | 22                                              |
| children                         | 3.0-4.0                |                     | 18                                              | 31                                              |
| child (3 years old)              | 2.0-3.0                |                     | 26                                              | 45                                              |

Analyzing the results presented in the above table, it is revealed that within less than 4 hours even in a large cavity where there fit even 15 people, the e-nose system would be able to detect a 3 years old child, assuming that the weather conditions do not create fresh air flow rate more than $1.2 \text{m}^3/\text{min} (F_e = n \cdot F_{fe} \cdot F_e)$. Weather conditions and their influence to the flow rate of fresh air coming into the cavity, they are analyzed in another paper.

5. Conclusions

In this paper, the performance of a mobile e-nose system was studied. The targeted e-nose system it measures the atmospheric air gas components’ concentrations (actually CO₂ and O₂), into a rubble void, where humans are entrapped, after a disastrous event that caused the collapsing of a building/construction. The performance of the sensors of the system was formulated to determine the equations calculating the anticipated concentration of CO₂ and O₂ into a void/cavity as a function of time. Then the anticipated performance of such a system was examined considering various cases with parameters like the kind of entrapped humans in a void, the characteristics of the CO₂ and O₂ sensors.
and their noise floor detection limits, and the kind of void apertures. In all cases there were identified the expected levels of CO$_2$ and O$_2$ to estimate the capabilities of detection of the presence of humans in a rubble void by a mobile e-nose system with sensors of a specific sensitivity and specificity.

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7. References
[1] P. Brimblecombe, *Air: composition & chemistry*. Cambridge Cambridgeshire ; New York: Cambridge University Press, 1986.
[2] D. Colinetlagneaux and J. Troquet, "Development of Gaseous Composition of Exhaled Air in Man during Calm and Forced Breathing," *Archives Internationales De Physiologie Et De Biochimie*, vol. 80, pp. 775-+, 1972.
[3] G. M. Saidel and J. S. Lin, "Transport Abnormalities from Single-Breath Dynamics of Ar, Co2 and O2," *Respiration Physiology*, vol. 64, pp. 253-266, Jun 1986.
[4] A. A. Shusterman, V. E. Teige, A. J. Turner, C. Newman, J. Kim, and R. C. Cohen, "The BErkeley Atmospheric CO2 Observation Network: initial evaluation," *Atmospheric Chemistry and Physics*, vol. 16, pp. 13449-13463, Oct 31 2016.
[5] S. J. Aukburg, G. R. Neufeld, S. Levine, and P. W. Scherer, "Effective Diffusing Area (Eda) Derived from Single Breath O-2 and Co-2 Exhalation Curves Compared," *Federation Proceedings*, vol. 44, pp. 1581-1581, 1985.
[6] H. Yamagishi, Y. Tohjima, H. Mukai, Y. Nojiri, C. Miyazaki, and K. Katsumata, "Observation of atmospheric oxygen/nitrogen ratio aboard a cargo ship using gas chromatography/thermal conductivity detector," *Journal of Geophysical Research-Atmospheres*, vol. 117, Feb 28 2012.
[7] J. Badawy, O. K. Nguyen, C. Clark, E. A. Halm, and A. N. Makam, "Is everyone really breathing 20 times a minute? Assessing epidemiology and variation in recorded respiratory rate in hospitalised adults," *BMJ Qual Saf*, vol. 26, pp. 832-836, Oct 2017.
[8] A. Rodriguez-Molinero, L. Narvaiza, J. Ruiz, and C. Galvez-Barron, "Normal respiratory rate and peripheral blood oxygen saturation in the elderly population," *J Am Geriatr Soc*, vol. 61, pp. 2238-40, Dec 2013.
[9] S. Fleming, M. Thompson, R. Stevens, C. Heneghan, A. Pluddemann, I. Maconochie, *et al.*, "Normal ranges of heart rate and respiratory rate in children from birth to 18 years of age: a systematic review of observational studies," *Lancet*, vol. 377, pp. 1011-8, Mar 19 2011.
[10] F. Ratjen, R. Jensen, M. Klingel, R. McDonald, C. Moore, N. Benseler, *et al.*, "Effect of changes in tidal volume on multiple breath washout outcomes," *PLoS One*, vol. 14, p. e0219309, 2019.
[11] S. L. DeBoer, *Emergency newborn care*: Trafford on Demand Pub, 2004.
[12] W. Q. Lindh, M. Pooler, C. D. Tamparo, B. M. Dahl, and J. Morris, *Delmar's comprehensive medical assisting: administrative and clinical competencies*: Cengage Learning, 2013.
[13] G. Yuan, N. A. Drost, and R. A. McIvor, "Respiratory rate and breathing pattern," *McMaster University Medical Journal*, vol. 10, pp. 23-25, 2013.
[14] A. Anyfantis and S. Blionas, "Design and Development of a Mobile e-nose platform for Real Time Victim Localization in Confined Spaces During USAr Operations," in *2020 IEEE International Instrumentation and Measurement Technology Conference (I2MTC)*, 2020, pp. 1-6.
[15] A. Anyfantis and S. Blionas, "Indoor air quality monitoring sensors for the design of a simple, low cost, mobile e-nose for real time victim localization," presented at the PACET 2019, Volos, Greece, 2019.