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EMBEDDED SENSING AND ACTUATION FOR HELMETS CO2 LEVELS CONTROL

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Abstract- The paper reports on the development and evaluation of a simple closed loop solution for controlling the CO2 levels within small enclosed environments, such as Explosive Ordnance Disposal (EOD) protective suit helmets. Based on a detailed analysis of the helmet environment during bomb disposal missions, the solution proposed automates the current manually controlled fan integrated within the helmet to achieve an effective, timely and energy efficient, control system.

Whilst the paper and its supporting experimental work focus on the particular case study of operatives wearing EOD suit helmets, the methods proposed and the control system development methodology are generic and directly applicable to a wide class of helmet usage scenarios.

The main contributions in the paper are as follows: i) the design and implementation of an empirical helmet model based on data collected with a bespoke helmet embedded instrument developed by the authors; and ii) the production of a simple but effective fan air flow control algorithm for containing CO2 concentration exposure during missions, and an associated evaluation simulator/test bed. The resulting closed loop, automated sensing and actuation system extends the otherwise short fan battery lifetime to cover entire missions, delivers a healthy breathing environment for the operative and minimises noise disruption associated with the use of the fan. The control algorithm outperforms fixed airflow settings in terms of energy efficiency.

Figure 1: Explosive Ordnance Disposal suit.

I. INTRODUCTION

The concentration of CO_2 in Explosive Ordnance Disposal (EOD) suit helmets is an important factor in the safety and comfort of personnel wearing EOD suits. The authors' previous experimental studies showed that CO_2 levels within EOD suit helmets (worn during bomb disposal missions) become excessively high within a few minutes of wearing the suit and helmet. A combination of factors lead to little natural ventilation within the helmet: i) unlike a motorcyclist, the EOD operative is generally moving at low speed; ii) the suit itself, with its high protective collar and stiff padding, forms a barrier to airflow (see figure 1); iii) the operative is physically and physiologically active (simply wearing the 40 kg suit is somewhat strenuous) and thus expiring a greater proportion of CO_2 than when at rest.

The stuffiness caused by high levels of CO_2 is not simply an inconvenience; prolonged exposure to elevated CO_2 could impair the wearer physically and mentally and may endanger the mission. In response to a previously identified problem with potential heat stress when wearing the suit, a UK EOD suit manufacturer developed an innovative solution: fitting, within the suit, manually controlled and battery operated fans that can deliver up to 200 ℓ/min of cooled air into the operative's back and helmet. The airflow provides some cooling of the face, and ensures air in the helmet is circulated with the air outside, thus lowering the CO_2 concentration. The CO_2 concentration within the helmet can be quantified given an appropriate sensing system (such as the one developed by the authors here), but there are also several other factors that need to be considered when making use of cooling fans: i) the potential to distract the wearer of the EOD suit is high given the level of noise created by the fan when run at a high speed setting; ii) the action of starting and stopping the fan will also distract the wearer from the mission to some extent; iii) private communications with an EOD suit manufacturer showed that the power supply for the fan (based on non-rechargeable batteries) is not necessarily able to sustain high fan speeds for the entire duration of a mission, requiring that a trade off is found to conserve power but also allow for higher speed operation when needed; iv) the posture of the wearer, which has been observed to allow more or less airflow into the helmet depending on the exact position of the head. The work here makes use of suit integrated airfans and attempts to optimise their usage in terms of the fan battery life, the inconvenience of operating the fan manually during missions, and the noise generated by its use.

Exposure to raised levels of CO_2 in generic enclosed environments are a known Occupational Health and Safety risk, considered in a variety of standards and publications. Carbon dioxide makes up approximately 0.04 % of normal outdoor air [24] and between 0.09 % and 0.25 % of indoor air [20]. In air exhaled by humans the concentration is approximately 4.5% [23]. Inhaled air concentrations of around 3 % to 5 % cause occasional dizziness, increased depth and rate of breathing, increased blood pressure, reduced hearing acuity, and headaches. In greater concentrations it causes more persistent dizziness, sweating, restlessness, disorientation, and visual distortion [5, 16, 25]. Long-term exposure to elevated CO_2 concentrations can cause drowsiness, fatigue, muscle pain, persistent headaches and reduced performance levels [6, 13].

In terms of safe CO_2 concentrations, the Occupational Safety and Health Administration (OSHA) [17], the American Conference of Governmental Industrial Hygienists (ACGIH) [1], and the National Institute for Occupational Safety and Health (NIOSH) [15] all specify that 5,000 ppm (0.5 %) should be the maximum time-weighted mean exposure level over the duration of an eight hour work day. ACGIH and NIOSH further specify the short-term (15 minute) exposure limit as 30,000 ppm (3 %), though Schaefer [19] reported that “submarine personnel exposed continuously at 30,000 ppm were only slightly affected, provided the oxygen content of the air was maintained at normal concentrations”. In an environment such as the EOD suit helmet, where there is no regulation of oxygen content, it is almost certain that higher CO_2 concentrations will lead to lower oxygen concentrations, as demonstrated by Brühwiler *et al.* [4].

There are known problems with the buildup of CO_2 within helmets generally, from motorcyclist helmets [4] to surgery ones [18] and consequences of wearers’ exposure to increased concentration of CO_2 range from mild drowsiness, to cognitive impairment [3], to mission aborts due to safety concerns [12]. Despite this, helmets have not been extensively researched and models of CO_2 build-up do not exist, despite the use of wireless sensing devices in other areas to limit the exposure of human subjects to dangerous conditions [2, 14, 22]

A reason for the small number of works in this area could be the lack of easy to use, portable and untethered instrumentation for in field quantification of helmet environments. Laboratory instruments as used in the sports science field often require a face mask, lengths of tubing, and a large external measurement unit (see as an example, the unit used by Brühwiler *et al.* [4]). Additionally, some helmet modification are required in order to accommodate the probes. In response to this, the authors here firstly engaged with the development of a MEMS based, helmet integrated instrument to enable accurate CO_2 data collection and further to support the closed loop sensing and fan actuation system. The instrumentation developed is described in Section II. With regard to future monitoring systems of this type, however, advances in robotics and disaster management technologies are likely to drive development of field deployable, miniature, unthethered breath analysis systems [21].

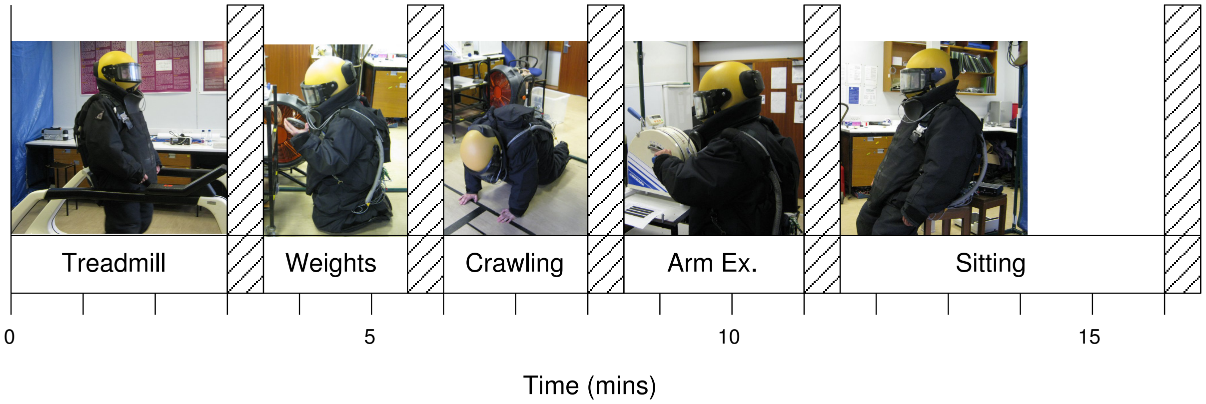

Figure 2: Standard protocol used for experimentation (showing one of four identical cycles).

The paper is structured as follows: Section 2 details the laboratory trials conducted and the instrumentation used for data gathering, Section 3 provides some analysis of the experimental data and describes the model developed for simulating helmet CO_2 concentration, Section 4 describes the algorithm developed for autonomous fan control towards containing the helmet CO_2 concentration within defined bounds, Section 5 provides an evaluation of the helmet CO_2 model and fan control algorithms, and Section 6 gives some concluding discussion.

II. LABORATORY TRIALS AND HELMET INSTRUMENTATION

Laboratory trials were performed based on the mission-like protocol illustrated in Figure 2. Six participants undertook four activity cycles lasting 16.5 minutes each and consisting of walking on a treadmill (3 mins), kneeling while moving weights from one place to another within reaching distance (2 mins), a crawling and searching activity (2 mins), arm cranking (2.5 mins), and seated physical rest (4.5 mins). There were 30 second intervals between each activity in order to allow for transition between activity stations. Ambient air temperature was maintained at 20 °C during the protocol. The six subjects underwent three trials each with a cooling fan providing a flow r_f of either 0 ℓ/min, 50 ℓ/min, or 100 ℓ/min to the helmet. The trials were ordered differently for each subject to avoid changes in flow rate being correlated with the gradual acclimatisation of subjects over the trials. Each subject also had a one week separation between trials to ensure that subjects are rested or at least not overly affected by the previous trial. The flow from the fan was directed into the helmet from below (not delivered directly into the helmet), so the actual flow into the helmet was dependent on the posture of the subject. For example, looking upwards allowed more flow into the helmet than looking downwards. Three of the subjects had not previously performed trials wearing the EOD suit and thus performed an additional acclimatisation trial.

The data for Subject 2 was excluded from the aggregate analysis presented here (and only included where results are given per-subject). For this subject, the helmet did not fit well, and this appears to have caused a significant difference in the measured CO_2 levels as shown in

Figure 3: CO_2 sensor positioning within the EOD suit helmet.

Table 1 (particularly for zero fan flow $r_f = 0$).

The instrument designed by the authors for sensing in-helmet CO_2 concentrations was deployed throughout the trials described above[1]. The node hardware platform used is described elsewhere [8]. In summary, it is composed of Gumstix Verdex embedded computing devices paired with in-house produced expansion boards for sensor connectivity. The CO_2 sensor used is a Gas Sensing Solutions C20 sensor, with a sensing range of 0 ppm to 200,000 ppm and a resolution of 10 ppm. Figure 3 shows the position of the CO_2 sensor within the helmet. The sensor senses the CO_2 concentration, converts this from the raw analogue signal into a value in parts per million, adjusts the value according to the loaded calibration constants, and transmits a string containing the ASCII representation of the value to a node (located within the EOD suit) via a wired serial connection. The node checks the data for error conditions (such as out of range values), packages the data for transmission, and transmits via a wireless Bluetooth connection to a base station. The node within the EOD suit is also responsible for actuating the in-suit cooling system via an in-house interface board that replaces the existing manual control system. Section IV describes the control algorithm developed for this purpose.

III. EMPIRICAL HELMET CO_2 MODEL

a. Parameters And Data Dependencies

The data gathered from the trials described above was firstly examined to determine: the effect of different fan airflow levels on the CO_2 concentration, and the effect of activity type on the CO_2 concentration.

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[1] A commercial data logger was used to log skin and core temperature data during the treadmill, arm exercise, and sitting phases of each cycle. At these times, the subject was also asked to report their thermal sensation and thermal comfort, along with several other health and comfort related questions such as nausea, headaches, and helmet stuffiness. The temperature and sensation data was not used in the analysis in this paper, but was used in other work by the authors [7, 9, 10].

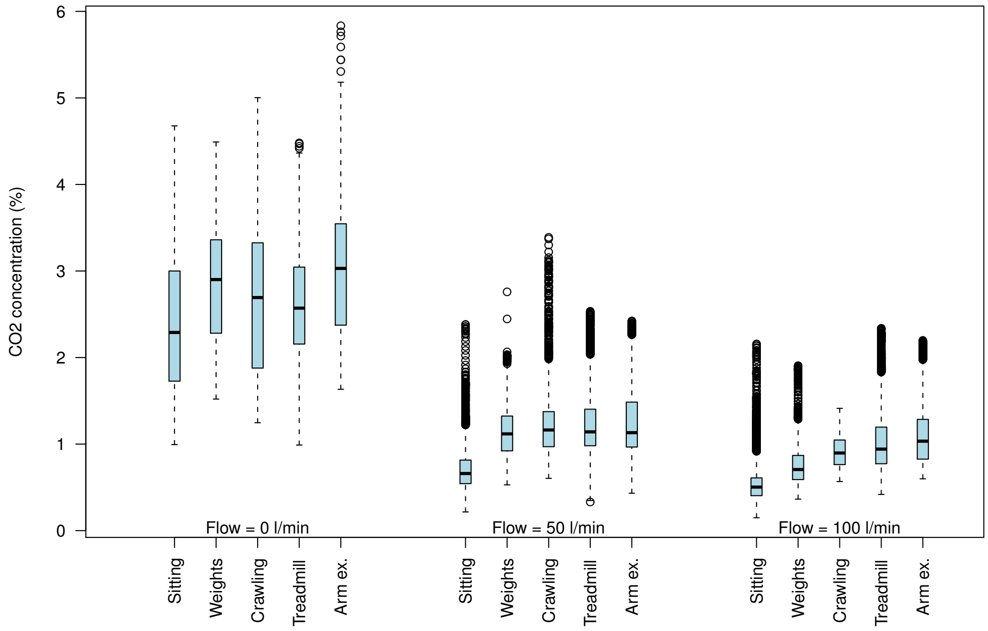


Figure 4: Overall distribution of CO_2 concentrations for six subjects undergoing a mission-like protocol with the fan set to three different flow settings (0 ℓ/min, 50 ℓ/min, and 100 ℓ/min). Activities are ordered according to increasing CO_2 concentrations at the 50 ℓ/min and 100 ℓ/min settings.
For each activity and flow combination the box represents the 1st to 3rd quartile range for the CO_2 concentrations, the thick horizontal line represents the median value, the upper and lower bars represent the minimum and maximum values, and the circles represent outlying values. Outlying values are defined to be those that are greater than 1.5 times the interquartile range away from the 1st and 3rd quartiles.

a.i Relationship Between Fan Flow And CO_2 Concentration

Figure 4 shows the overall distribution of CO_2 concentrations for six subjects undergoing the mission-like protocol with the fan set to three different fan flow settings r_f of 0 ℓ/min, 50 ℓ/min, and 100 ℓ/min. While the 50 ℓ/min setting provides a large benefit over having no airflow, in most cases the 100 ℓ/min setting provides little to no benefit beyond this. Figure 5 demonstrates this with data gathered from one subject performing the mission-like protocol with the fan at each speed setting. The concentrations observed for each subject and overall are summarised in Table 1. The table shows that when the flow rate is 50 ℓ/min, the CO_2 concentration will be maintained, on average, at around 1.0 %—a large reduction in CO_2 levels compared with the mean of 2.4 % at $r_f = 0$ ℓ/min. However, when the flow rate is then increased to 100 ℓ/min, the mean only decreases slightly further to 0.8 %.

When the cooling fan is not used the CO_2 concentration often exceeds the safety limits described in Section I. On average, the total time spent at CO_2 concentrations above 3 % was around 14 minutes when the cooling fan was not used in a 66 minute trial. With $r_f = 50$ ℓ/min

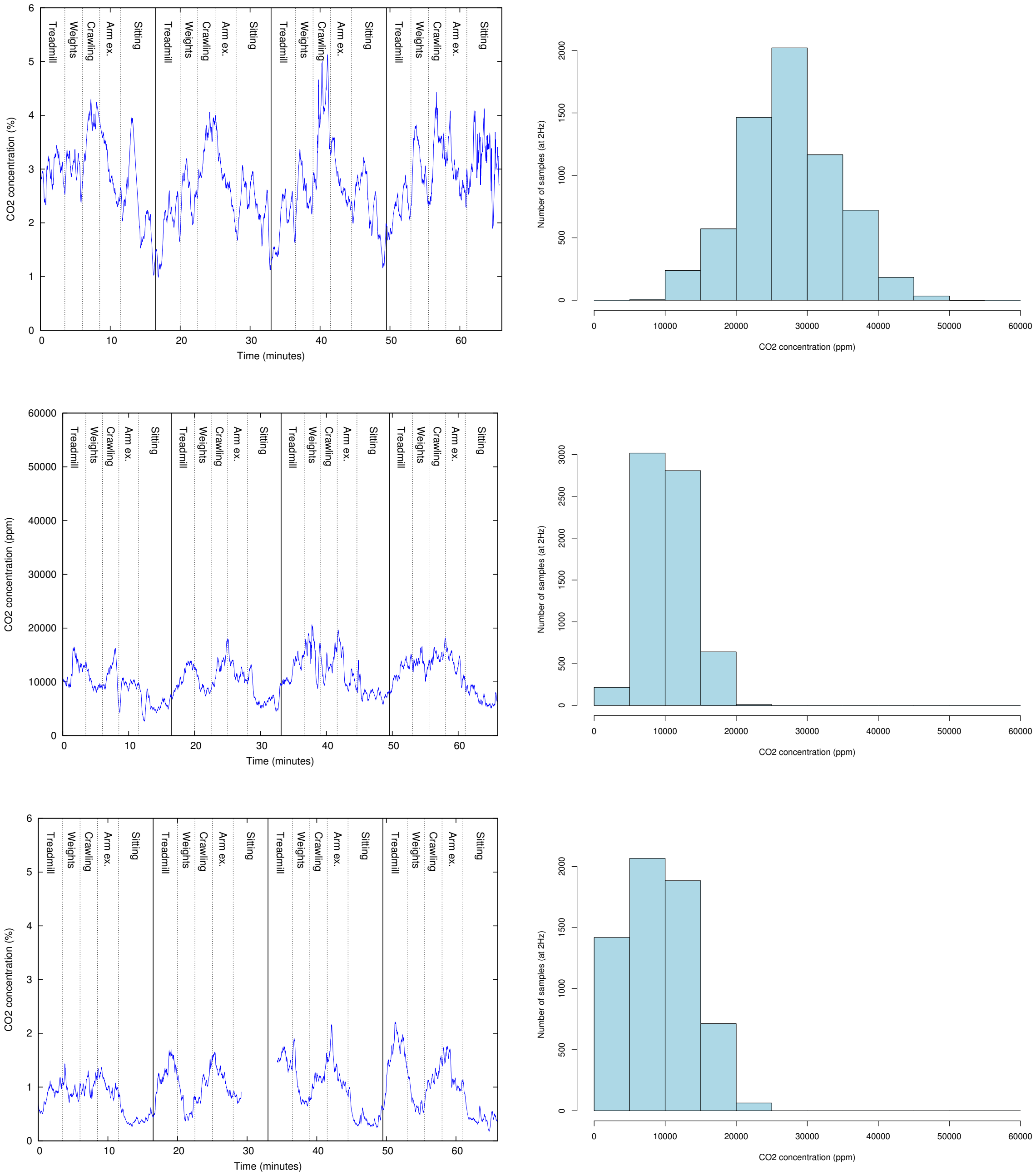


Figure 5: Helmet CO_2 concentrations during experimentation for a subject during a trial with no airflow (top), 50 ℓ/min airflow (middle), and 100 ℓ/min airflow (bottom). Some data was lost during the 100 ℓ/min trial due to changing batteries.

Table 1: Summary of CO_2 concentrations (mean ±SD in %) observed for each fan setting per subject and overall.

	Fan flow r_f (ℓ/min)		
Subject	0	50	100
1	2.1 ±0.6	1.2 ±0.5	0.8 ±0.4
2	1.5 ±0.3	0.9 ±0.2	0.8 ±0.3
3	3.0 ±0.7	1.0 ±0.3	0.8 ±0.4
4	2.2 ±0.6	0.8 ±0.3	0.7 ±0.2
5	3.2 ±0.5	1.1 ±0.4	0.8 ±0.2
6	2.7 ±0.7	1.0 ±0.3	0.9 ±0.4
Overall	2.4 ±0.8	1.0 ±0.4	0.8 ±0.3

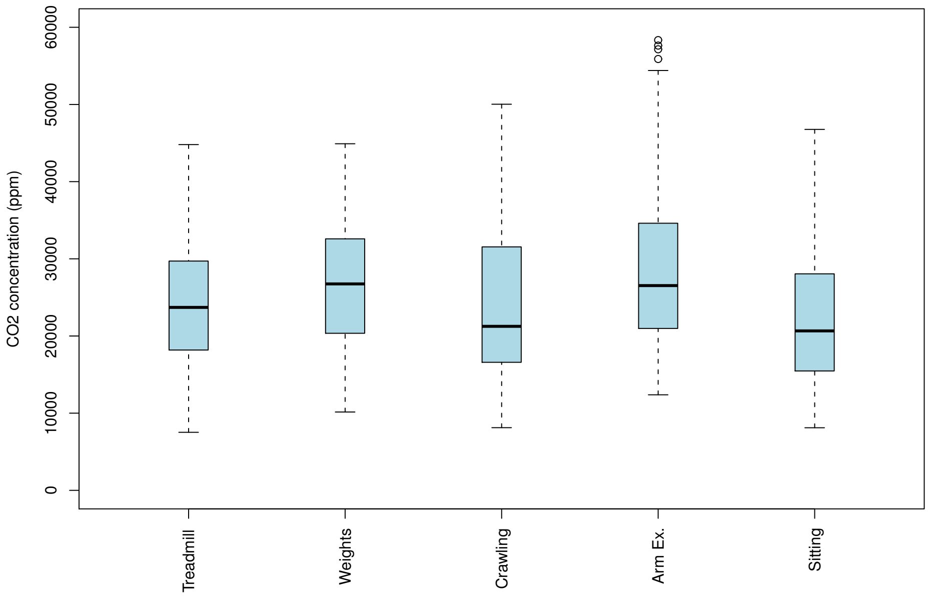
the total time was reduced to an average of 0.03 minutes, and at $r_f = 100$ ℓ/min the average was zero minutes. Another way of interpreting the safety limits on CO_2 exposure is in terms of the time-weighted average limit of a 0.5 % concentration. Given the average concentrations observed, the maximum mission time during an eight hour work day (in order to incur an average exposure of 0.5 % over the course of the day) is 1.4 hours at zero ℓ/min, 3.5 hours at 50 ℓ/min, and 4.5 hours at 100 ℓ/min. The limiting factor thus remains the battery life for the high airflows.

a.ii Relationship Between Activity Type And CO_2 Concentration

It is conceivable that the CO_2 concentration within the helmet may be affected by the activity being performed, due to differences in breathing rate, breathing depth, and the flow of ambient air into the helmet. No particular activity was seen to consistently result in a higher CO_2 concentration across all subjects. The activities most frequently associated with higher CO_2 concentrations were crawling, walking on a treadmill, and standing performing arm exercise. Figures 6, 7, and 8 show a) boxplots of the data values observed during each activity, b) summary statistics per activity, and c) the results of two-tailed t-tests comparing the data values observed during each activity (with a null hypothesis h_0 that the true difference in means for the two sets of data in each case was zero). The three figures correspond to a r_f of 0 ℓ/min, 50 ℓ/min and 100 ℓ/min. It can be seen that for $r_f = 0$ ℓ/min, the t-tests determined that there was significant difference between all activities with the exception of the treadmill and crawling activities, for which h_0 could not be rejected. For $r_f = 50$ ℓ/min this was also true of the arm exercise when compared with the treadmill and crawling activities. For $r_f = 100$ ℓ/min, h_0 was rejected for all combinations of activities.

b. Flow-Based Model Of Helmet CO_2 Concentration

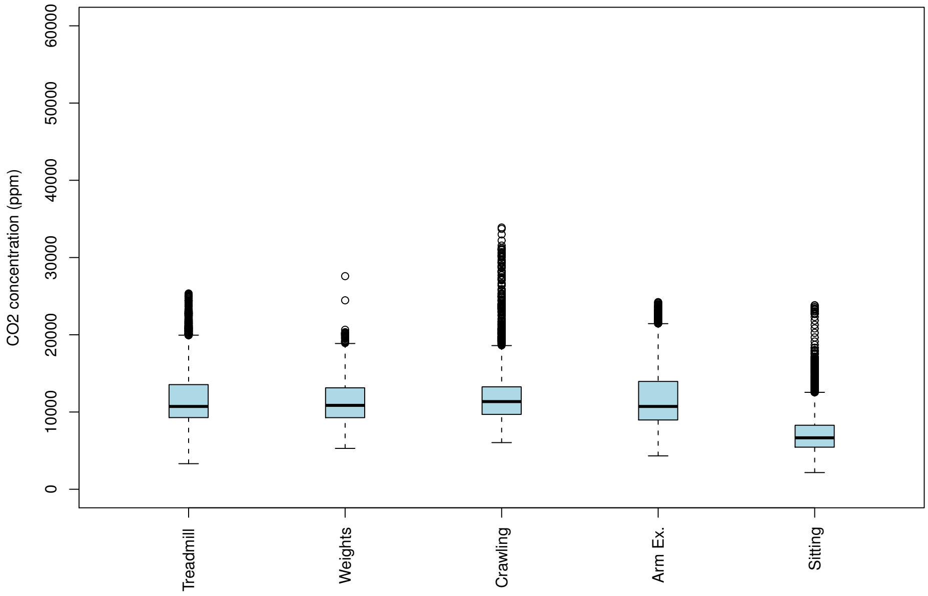
To enable the development and evaluation of suitable control algorithms for this application, an empirical helmet model was built and a closed lop simulator implemented embedding the



	CO_2 concentration (%)			
Activity	Min	Mean	Max	SD
Treadmill	1.0	2.6	4.5	0.6
Weights	1.5	2.9	4.5	0.6
Crawling	1.2	2.7	5.0	0.8
Arm Ex.	1.6	3.0	5.8	0.7
Sitting	1.0	2.4	4.7	0.8

	Treadmill	Weights	Crawling	Arm Ex.	Sitting
Treadmill	-	$< 2.2 \times 10^{-16}$	0.10	$< 2.2 \times 10^{-16}$	$< 2.2 \times 10^{-16}$
Weights		-	$< 2.2 \times 10^{-16}$	9.27×10^{-16}	$< 2.2 \times 10^{-16}$
Crawling			-	$< 2.2 \times 10^{-16}$	$< 2.2 \times 10^{-16}$
Arm Ex.				-	$< 2.2 \times 10^{-16}$
Sitting					-

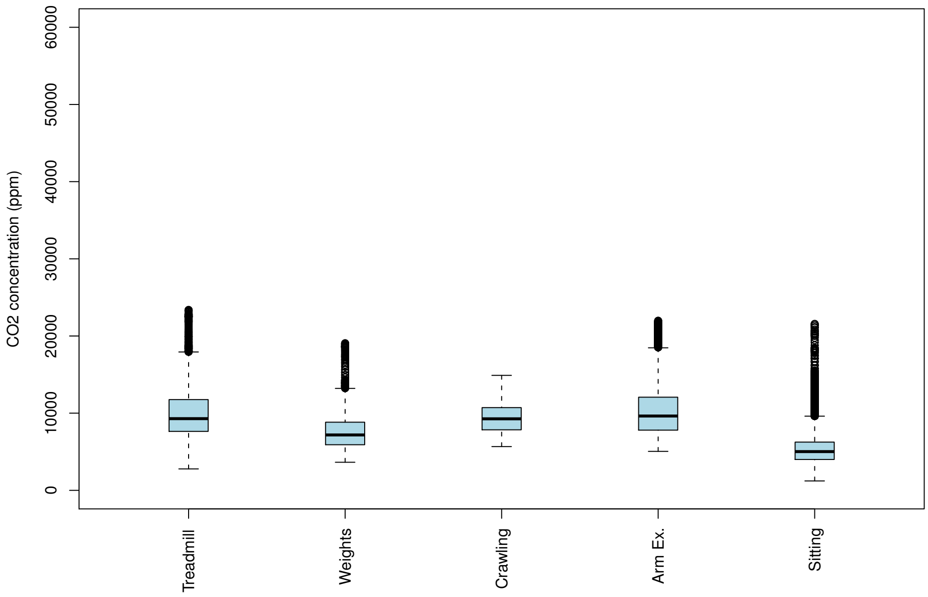
Figure 6: Summary of CO_2 concentrations for each activity with a fan flow of 0 ℓ/min.



	CO_2 concentration (%)			
Activity	Min	Mean	Max	SD
Treadmill	0.3	1.2	2.5	0.4
Weights	0.5	1.1	2.8	0.3
Crawling	0.6	1.2	3.4	0.4
Arm Ex.	0.4	1.2	2.4	0.4
Sitting	0.2	0.7	2.4	0.2

	Treadmill	Weights	Crawling	Arm Ex.	Sitting
Treadmill	-	$< 2.2 \times 10^{-16}$	0.19	0.89	$< 2.2 \times 10^{-16}$
Weights		-	$< 2.2 \times 10^{-16}$	1.19×10^{-14}	$< 2.2 \times 10^{-16}$
Crawling			-	0.28	$< 2.2 \times 10^{-16}$
Arm Ex.				-	$< 2.2 \times 10^{-16}$
Sitting					-

Figure 7: Summary of CO_2 concentrations for each activity with a fan flow of 50 ℓ/min.



	CO_2 concentration (ppm)			
Activity	Min	Mean	Max	SD
Treadmill	0.4	1.0	2.3	0.4
Weights	0.4	0.7	1.9	0.2
Crawling	0.6	0.9	1.4	0.2
Arm Ex.	0.6	1.1	2.2	0.4
Sitting	0.1	0.5	2.2	0.2

	Treadmill	Weights	Crawling	Arm Ex.	Sitting
Treadmill	-	$< 2.2 \times 10^{-16}$	$< 2.2 \times 10^{-16}$	7.35×10^{-11}	$< 2.2 \times 10^{-16}$
Weights		-	$< 2.2 \times 10^{-16}$	$< 2.2 \times 10^{-16}$	$< 2.2 \times 10^{-16}$
Crawling			-	$< 2.2 \times 10^{-16}$	$< 2.2 \times 10^{-16}$
Arm Ex.				-	$< 2.2 \times 10^{-16}$
Sitting					-

Figure 8: Summary of CO_2 concentrations for each activity with a fan flow of 100 ℓ/min.

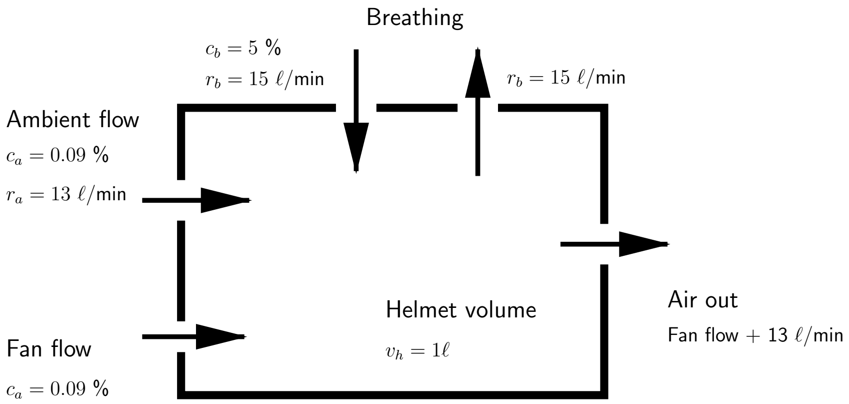


Figure 9: Modelled air flows into and out of the EOD suit helmet.

Table 2: CO_2 simulation parameter values. * Determined via regression and selected based on activity type.

Ambient flow		Breathing		Fan flow	Helmet
c_a	r_a	c_b	r_b	m_f	v_h
0.09 %	*	5 %	*	0.85	1 ℓ

model and the control in a closed loop fashion. The simulator acted as a test bed for evaluating a simple control algorithm and comparing it with the performance of fix flow settings.

This section first describes the factors affecting the concentration of CO_2 within the EOD suit helmet; next the simulation model is introduced; the flow-based component of the simulation is described, and the addition of a random walk component is justified.

b.i Factors Affecting Helmet CO_2 Concentration

There are several factors affecting the CO_2 concentration within the EOD suit helmet, summarised in Figure 9. The exhaled and ambient CO_2 concentrations were based on values reported in the literature, the output of the cooling fan was measured prior to experimentation, the helmet volume was estimated, and the subject breathing rate and exchange of air between the helmet and ambient air were based on regression results using experimental data. Different subject activities cause different breathing rates and rates of air exchange to be selected. The values (or method for setting) each parameter of the proposed model are summarised in Table 2.

b.ii Modelling Of Helmet CO_2 Concentration

Modelling of the EOD suit helmet CO_2 concentration is performed based on:

1. The flows described in Section III.b.i. These determine the expected CO_2 concentration at any timestep.

2. A random walk based on varying the acceleration of a signal according to a Gaussian

distribution. This provides variation away from the "average" value determined by the flow-based aspect of the model.

These two aspects of the model are described in the following sections. Each provide a change in CO_2 concentration at every timestep ($\Delta c_{h,m}$ and $\Delta c_{h,w}$ respectively). These values are summed with the previous concentration.

b.iii Expected Helmet CO_2 Concentration

Based on the flows presented in Section III.b.i, a model is generated to calculate the expected change in concentration of CO_2 within the EOD suit helmet: $\dot{c}_h$. The flows into the helmet consist of: exhaled air at the specific exhaled air concentration, output from the fan at ambient concentration, and ambient flow at the ambient concentration. Flows out of the helmet consist of the inhaled air and additional flows to balance the fan output and ambient flow into the helmet, all at the concentration of the air currently in the helmet. The overall effect of these flows is scaled based on the volume of the helmet. The model calculation is thus as follows:

$$\dot{c}_h = \frac{c_b r_b + c_a\left(m_f r_f + r_a\right) - c_h\left(r_b + m_f r_f + r_a\right)}{v_h}$$

where

- c_h, c_b and c_a are the CO_2 concentration in the helmet, exhaled air, and ambient air respectively,
- r_b, r_f, and r_a are the flow rates for breathing, the fan output, and ambient exchange respectively,
- m_f is the fan flow modifier, and,
- v_h is the helmet dead space volume.

The diffusion of CO_2 from the in-flowing sources is assumed to be instantaneous within the helmet volume. This model is expected to be a reasonable approximation of the factors affecting CO_2 concentration in the helmet, though due to additional factors not accounted for, the parameters may include the effects of multiple real-world factors.

The model will provide a stable CO_2 concentration when $\dot{c}_h = 0$, resulting in an *expected* concentration $\hat{c}_h$ determined by

$$\hat{c}_h = \frac{c_b r_b + c_a\left(m_f r_f + r_a\right)}{r_b + m_f r_f + r_a}$$

Given experimental results for helmet concentrations c_h and fan flow rates r_f and setting as constant some of the variables, it is possible to solve for other unknowns using the least squares method.

Table 3: Final fit values for r_a and r_b per activity.

	Treadmill	Weights	Crawling	Arm exercise	Sitting
r_a (ℓ/min)	18.2	9.3	12.8	10.4	6.7
r_b (ℓ/min)	19.3	14.1	18.3	16.4	7.1

The model approximates the mean CO_2 concentrations observed in the EOD suit helmet during experimentation, but does not reflect the variation around the mean observed experimentally. Such variation is partly due to the subject performing different activities (which modify some of the model parameters—the most likely being the ambient flow and the breathing rate) and partly due to factors such as the CO_2 slowly diffusing within the helmet over time rather than instantaneously. Some of the variation observed must be modelled in order to provide a useful simulation for testing of fan control algorithms. This is modelled in two ways: by varying the r_a and r_b parameters according to the activity type being simulated (described in Section III.b.iv) in conjunction with a random walk process (described in Section III.b.v).

b.iv Selection Of Activity-Based Parameters

As noted previously, estimates for ambient flow rate r_a and breathing rate r_b were determined using data from the experimental trials described in Section II and fitted against the model presented in Section III.b.iii. This fitting was performed for each activity using the data gathered for subjects 3, 4, 5, and 6. The data from subjects 1 and 2 were excluded as the fitted parameters (when examined per subject) were significantly different to subjects 3 to 6 (who were quite similar). For example, in the arm exercise activity, the determined ambient flow rate r_a for subjects 3 to 6 had a mean of 11.2 ℓ/min and a standard deviation of 5.2. For subject 1, the ambient flow (to fit the data) was 52.6 ℓ/min and for subject 2, it was 30.7 ℓ/min. The different results are expected to be due to the particular physiques of subjects 1 and 2, as described previously. The model is intended to represent an "average" person, and thus only the data for subjects 3 to 6 was used.

Least squares regression was used to find ambient and breath flow rates, r_a and r_b, using measured helmet CO_2 concentrations c_h and fan flow rates r_f over each activity. The final values are summarised in Table 3. The output of the flow-based portion of the model is shown in Figure 10. This demonstrates the model performed four cycles, each containing the five activities given. Each activity is sustained for three minutes, and for the first 30 seconds of each activity, r_a and r_b are linearly interpolated between the values for the previous and current activity to provide a more gradual transition.

b.v Adding Variation Via A Random Walk

In examining the experimental CO_2 data, it became clear that, in general, the rate of change of the concentration at time t tends to lie within a distribution based on the rate of change at $t-1$.

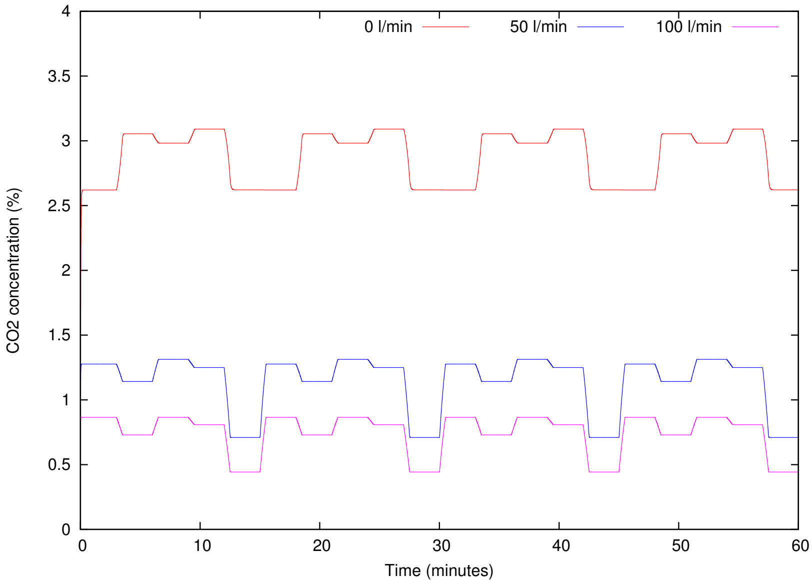


Figure 10: EOD helmet CO_2 concentration determined by the flows portion of the simulator for three fixed values of fan flow.

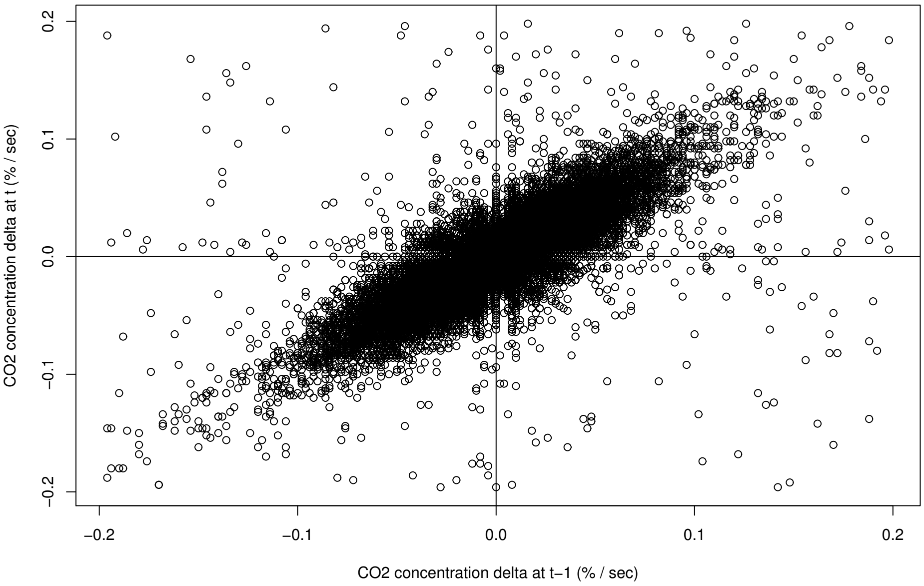


Figure 11: Rate of change of CO_2 concentration at time t compared to rate of change at $t-1$.

Mean μ	
x	y
6.881×10^{-7}	6.855×10^{-7}

Covariance		
	x	y
x	1.5450×10^{-8}	1.2194×10^{-8}
y	1.2194×10^{-8}	1.5449×10^{-8}

Correlation ρ
0.789

Figure 12: Parameters of the bivariate Gaussian based on rate of change of helmet CO_2 concentration at $t-1$ (x) and t (y).

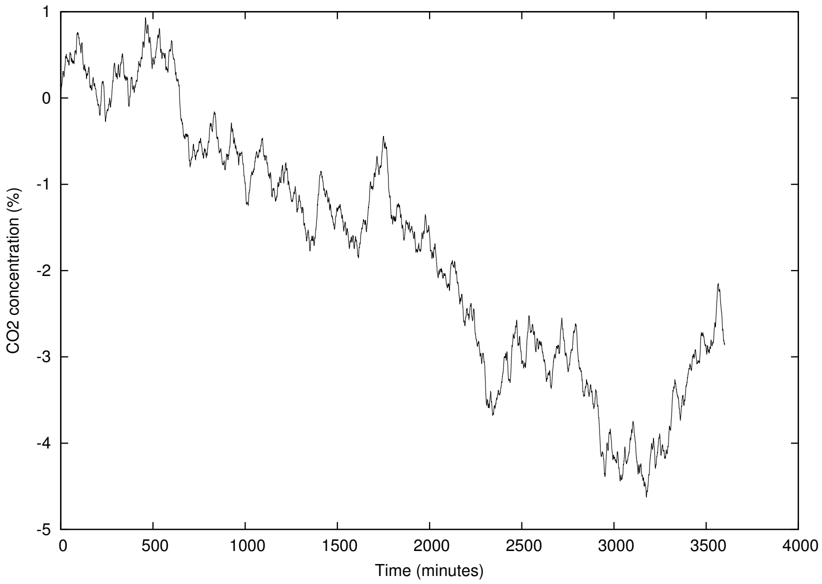


Figure 13: “Random walk” using a bivariate Gaussian to generate a new rate of change at each timestep.

This is demonstrated in Figure 11. Note that due to the sampling rate of the CO_2 sensor used, the period between $t-1$ and t is 0.5 seconds.

Based on this finding, a bivariate Gaussian can be generated using the rate of change at $t-1$ and t. This can then be used to generate a new rate of change at each timestep and thus perform a random walk. The bivariate Gaussian was created using the values given in Figure 12, based on the observed differences in rate of change from one timestep to the next. In this case, x refers to the rate of change at $t-1$ and y refers to the rate of change at t. The univariate Gaussian distribution for y given a particular value of x has a mean of $\mu_{y|x=x_0}$ and a variance of $\sigma^2_{y|x=x_0}$, which are calculated via:

$$\begin{aligned} \mu_{y|x=x_0} &= \mu_y + \rho\sigma_y \frac{x-\mu_x}{\sigma_x} \\ \sigma_{y|x=x_0} &= \sigma_y\sqrt{1-\rho^2} \end{aligned}$$

A value is randomly selected from this distribution as the new rate of change for the random walk at time t.

An example of the random walk being performed is shown in Figure 13. This does not respect any findings related to the range within which the CO_2 concentration is expected to lie, particularly in that it decreases to below 0 %. However, when combined with the flow-based portion of the model (which will attempt to "correct" the CO_2 concentration to the expected value), it produces results visually similar to those of the experimental data, including the cyclic nature of the results due to the protocol used. The effect of the flow-based portion of the model was scaled by a factor of 50 to prevent it from overwhelming the contribution of the random walk.

IV. AUTONOMOUS FAN CONTROL

Two strategies for controlling the cooling fan airflow into the EOD suit helmet in real time based on the measured CO_2 concentration were considered and compared: one based on fixed flow settings (further referred to as Algorithm 2) and one derived by considering the application wider constraints and optimisation criteria (further referred to as Algorithm 1):

- The concentration of CO_2 within the EOD suit helmet must be maintained at a low safe level to avoid the ill effects described in Section I.
- Higher fan speeds produce more noise, which has potential to distract the EOD suit wearer and block out other external noises. This caused some delays when subjects were asked the routine questions during experimentation. Outside the laboratory, this could become a more significant problem if the wearer of the EOD suit is expected to respond to audio cues, for example.
- Higher fan speeds produce more airflow across the face, which has been reported at different times as both distracting and as providing increased comfort. This is because thermal sensation is determined by more than just the local skin temperature; it also depends on the relative temperatures of other parts of the body [26] and the rate of change of temperature [11]. As the body overall can be assumed to be at a higher than usual temperature when wearing the EOD suit, the cooling effect of the fan airflow on the face translates into an improved thermal sensation and thermal comfort due to the lower relative temperature.
- Higher fan speeds cause a higher power consumption from the limited battery supply.

a. Control Algorithms Description

A stepping control algorithm, denoted `stepping_fan_control`, for controlling the flow rate r_f is given in Algorithm 1. At each timestep, the average CO_2 concentration over a window is calculated. If this average CO_2 is greater than the larger threshold, then the fan rate is increased. If it is smaller than the lower threshold, the fan rate is decreased. Otherwise, the fan speed is kept the same. The final value of r_f is bounded by the flow limits of the fan itself, in this case rounded to zero ℓ/min (turned off) and 200 ℓ/min.

Algorithm 1 Stepping algorithm for CO_2 fan control. Parameters for this algorithm consist of the step rate s, the minimum and maximum acceptable CO_2 $T_{\min}, T_{\max}$, and the maximum fan setting $r_{f,\max}$. SMA is a simple moving average with a window size of n.

```
stepping_fan_control($s, T_{\min}, T_{\max}, r_{f,\max}$)
    1. $c \leftarrow$SMA(current helmet $CO_2$ measurement, $n$)
    2. $r_f \leftarrow r_f + \begin{cases} -s & c < T_{\min}, r_f - s \geq 0 \\ s & c > T_{\max}, r_f + s \leq r_{f,\max} \\ 0 & \text{otherwise} \end{cases}$
    3. set flow rate to $r_f$
```

Algorithm 2 Fixed rate algorithm for CO_2 fan control. The only parameter is the fixed flow rate desired $r_{f,\text{fixed}}$.

```
fixed_fan_control($r_{f,\text{fixed}}$)
    1. set flow rate to $r_{f,\text{fixed}}$
```

A second strategy, given as Algorithm 2 and denoted `fixed_fan_control`, simply sets the flow rate to a fixed value. The main reason to consider this strategy is that if such an approach is found to perform as well as other strategies then it should be preferred as it does not require sensing or control logic.

Even while the CO_2 concentration is within the target zone, there are likely to be occasional transient increases in the readings which extend outside of the zone. Transient increases outside of the target zone such as this do not represent a danger to the suit wearer and would result in unnecessary fan speed changes. Additionally, if the modification of the fan flow rate was to cease as soon as the CO_2 concentration re-entered the target zone then it can be assumed that the concentration would be near one of the limits of the zone and would only require a small change in order to exceed the bounds again. Two measures are possible to help prevent these effects from occurring.

Activation delay An activation delay may be incorporated wherein the fan flow will not be modified unless the concentration is outside of the target zone for longer than a set duration. Due to the use of an averaging window over the input data, this delay was not deemed to be necessary.

Deactivation delay A deactivation delay may be incorporated wherein $\dot{r}_f$ is not immediately set to zero once the CO_2 concentration is within the target zone. For a number of seconds after the target zone is reached, the fan flow will be modified at half of the normal rate ($s/2$). This delay was used in the control algorithm.

b. Fan Control Algorithm Parameters

Fan Flow Step

The fan flow step s determines the rate at which the output of the fan will be modified. Setting this to a higher value results in a faster response to changes in concentration (thus counteracting them quicker) but also a larger response to transient data spikes. This parameter was set to a rate of 0.5 ℓ/min per second.

Target CO_2 Range

The target CO_2 concentration range, defined by T_{min} and T_{max}, provides a trade-off between maintaining a low CO_2 concentration in the helmet and preserving the fan battery life. Using a range rather than a specific value helps to prevent oscillation in the fan flow choice when the CO_2 concentration is around the target value. For the purpose of the evaluation given in Section V.b, the acceptable CO_2 concentration range was set to a target of 1.5 % ±0.5 %.

Data Window Size

A sliding averaging window of size n is applied to the CO_2 data. This helps to reduce oscillation in the control output by smoothing the input data. A window size of five seconds was chosen as a trade-off between reducing the noise in the data and responding correctly to actual changes.

Deactivation Delay

The delay chosen was five seconds, during which time the specified rate of change of fan output s is halved (to 0.25 ℓ/min per second).

V. MODEL AND CONTROL SYSTEM EVALUATION

a. Helmet CO_2 Model Evaluation

Evaluation of the helmet CO_2 model was performed with regard to two criteria:

1. The output of simulated data traces using the model should match the cyclic nature of the experimental data when the same activity protocol is specified.
2. The mean and standard deviation of the simulated CO_2 concentrations within each activity should be similar to those observed in the experimental data.

On inspection of the output of the helmet CO_2 model, it can be seen that the cyclic nature of the experimental data is visible in the simulated data trace, though the variation observed in the simulated trace is less than that in the experimental data. It should be noted that the simulated data trace is based on a protocol where each activity is performed for three minutes, giving 15 minutes per cycle, this is slightly different to the experimental protocol.

Table 4: Summary of experimental and simulated data traces per activity (at $r_f = 0$).

	Experimental		Simulated	
	Mean (%)	SD	Mean (%)	SD
Treadmill	2.64	0.61	2.54	0.45
Weights	3.06	0.54	2.88	0.28
Crawling	2.99	0.73	3.01	0.26
Arm ex.	3.11	0.62	3.06	0.23
Sitting	2.62	0.74	2.88	0.32

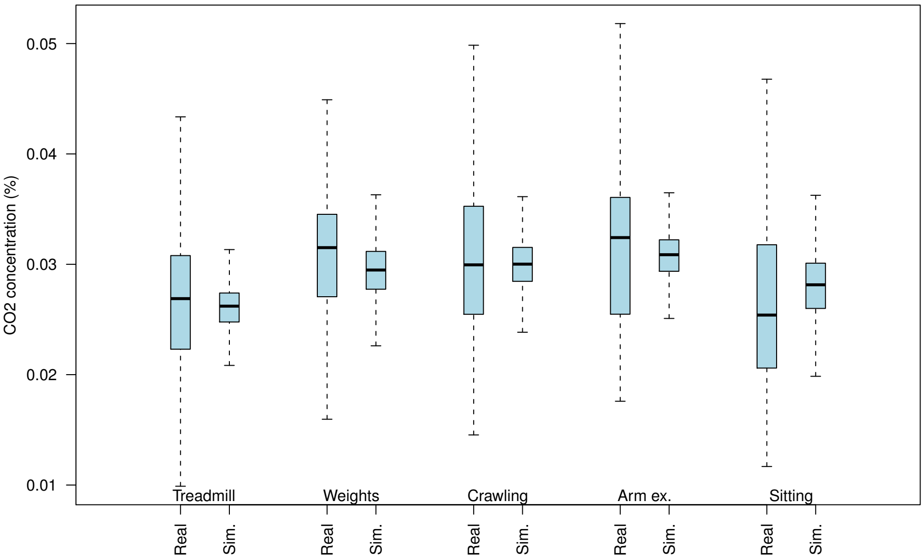


Figure 14: Boxplots for experimental and simulated helmet CO_2 concentrations.

Table 4 shows the means and standard deviation of the CO_2 concentration for each activity with a fan flow of 0 ℓ/min over:

- the experimental data for subjects 3 to 6, and,
- ten simulated data traces.

It can be seen that the simulated data traces give similar mean values to the experimental data, though the standard deviation of the simulation data is smaller than that of the experimental data for all activities. The largest difference between the experimental and simulated data appears to be for the weights and sitting activities, both of which give a mean of 2.88 % during simulation. Figure 14 represents these results graphically, showing boxplots of the experimental and simulated data ranges. The smaller variation in the simulated data can be seen here, as can the difference in means between the simulated and experimental data for the weights and sitting activities.

b. Control Algorithms Evaluation

In order to evaluate the fan control algorithm, the helmet CO_2 concentration simulator described in Section III.b was used. Several criteria were used in the evaluation of the algorithm:

Total litres of air delivered One of the aims of the fan control algorithm is to prolong the life of the battery packs powering the fans. In order to accomplish this, the fans should be set to the minimum flow rate required to effectively moderate the CO_2 concentration in the helmet. The flow rates over the course of a trial may be summarised by the total litres of air delivered by the fans.

Percentage of samples below target zone For a similar reason to the above, the CO_2 concentration samples that fall below the target zone represent a potential waste of battery power due to the fans being set to an unnecessarily high flow rate.

Percentage of samples above target zone The CO_2 concentration samples that fall above the target zone should be minimised in order to help protect the health of the operative.

The `stepping_fan_control` algorithm was evaluated against the target CO_2 concentration range and compared to `fixed_fan_control`. The fixed flow is representative of the effect of manual control of the fans, wherein the operative is likely to set a flow rate that feels effective to him at the start of the mission, and then leave the fan at that setting for the duration of the mission. Based on the simulation, the optimum fixed flow rate (given the data used in the creation of the helmet CO_2 model) is 25 ℓ/min. Thus, this flow rate was used to provide a challenging comparison for the `stepping_fan_control` algorithm. The `stepping_fan_control` and `fixed_fan_control` algorithms were both evaluated using a simulated mission-like protocol.

Table 5 presents the results of the evaluation over ten simulation iterations. It can be seen that on average, the `stepping_fan_control` algorithm delivers approximately the same total litres of air as `fixed_fan_control`. A greater percentage of the samples are above the target zone, though the lower standard deviation means that the results over different simulation runs are more consistently close to the mean than the results from `fixed_fan_control`. The result of 4.7% of values being above the target zone does not pose a significant problem to the operative, representing only slightly less than 3 minutes of an hour-long simulation. The `stepping_fan_control` control algorithm gives less samples below the target zone and, again, provides a lower standard deviation, and thus a more consistent result across different simulation runs. As a further observation, it can be seen that the `stepping_fan_control` control algorithm gives a similar number of samples above and below the target zone.

The `stepping_fan_control` algorithm is able to react to the helmet CO_2 concentrations regardless of the parameters of the simulation, whereas the fixed flow of 25 ℓ/min was selected specifically based on its performance with regard to the particular parameters selected. To demonstrate this, a further ten simulation runs were performed using both algorithms but with

Table 5: Results of the fan control algorithm evaluation over ten runs with a simulated mission-like protocol. Left: `stepping_fan_control` algorithm. Right: `fixed_fan_control`. AD = air delivered. TZ = target zone.

Run	AD (ℓ)	% Above TZ	% Below TZ
1	1575	5.3	4.7
2	1461	4.1	3.7
3	1640	5.3	4.7
4	1695	4.7	4.7
5	1612	4.1	4.0
6	1506	5.1	4.9
7	1571	4.3	4.7
8	1615	5.0	4.3
9	1588	3.9	3.6
10	1540	5.0	5.4
Mean	1580	4.7	4.5
SD	67	0.5	0.6

Run	AD (ℓ)	% Above TZ	% Below TZ
1	1500	2.9	5.0
2	1500	3.1	4.9
3	1500	6.7	5.7
4	1500	2.8	2.9
5	1500	5.2	2.7
6	1500	4.2	4.7
7	1500	3.9	6.1
8	1500	4.1	4.0
9	1500	5.5	2.1
10	1500	5.3	7.1
Mean	1500	4.4	4.5
SD	0	1.3	1.6

Table 6: Results of the fan control algorithm evaluation over ten runs with a simulated mission-like protocol using parameters fitted to subject 2's experimental data. Left: `stepping_fan_control` algorithm. Right: `fixed_fan_control`. AD = air delivered. TZ = target zone.

Run	AD (ℓ)	% Above TZ	% Below TZ
1	1886	8.4	7.4
2	1917	7.1	6.5
3	1890	7.6	7.0
4	1938	6.7	6.2
5	1930	7.0	6.0
6	1718	7.2	6.9
7	1836	7.2	7.5
8	1824	6.8	6.1
9	1832	6.3	5.9
10	1893	7.7	7.7
Mean	1866	7.2	6.7
SD	66	0.6	0.7

Run	AD (ℓ)	% Above TZ	% Below TZ
1	1500	16.6	3.3
2	1500	19.2	3.1
3	1500	16.5	3.3
4	1500	18.5	1.6
5	1500	17.6	1.4
6	1500	16.7	3.2
7	1500	17.0	4.0
8	1500	17.6	2.6
9	1500	16.1	1.1
10	1500	18.6	5.0
Mean	1500	17.4	2.9
SD	0	1.0	1.2

the simulation parameters determined for subject 2 (whose data was not used in calculating the parameters for the simulation used thus far). The results of this are given in Table 6. It can be seen that while the `stepping_fan_control` algorithm, with no modification, provides a worse performance than that seen in Table 5 (though with similar standard deviation / consistency), `fixed_fan_control` performs much worse in terms of the percentage of sample above the target zone. A fixed flow control method will only give good performance if the dynamic characteristics of the CO_2 concentration within the helmet are known prior to use.

VI. CONCLUSIONS

Based on a large number of experimental trials, the paper has established that:

- Helmet CO_2 concentration can be controlled via the use of the EOD suit helmet fan, though higher fan flow rates provide decreasing returns.
- Use of the fan to supply air to the helmet can significantly increase the time that an operative may be engaged with a mission without exceeding the workplace limits specified by OSHA, ACGIH, and NIOSH.
- The activity engaged with by the operative has a significant impact on the CO_2 concentrations experienced at all fan flow rates.
- The flow rate of the fan itself affects the wearer due to the noise generated and the increased thermal comfort at higher flow rates.
- Based on its performance in the simulations performed, the `stepping_fan_control` fan control algorithm proposed effectively controls the EOD suit helmet fan during use. A particular advantage of this fan control algorithm is its computational simplicity and that it can be implemented on a suit embedded processor with minimal computational resources.

While this investigation was performed within the context of the EOD suits, the findings may also be of use in several other fields such as sports science experimentation or commercial helmet products.

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