Identification and Control of an Oxygen Provider System for a Biological Capsule.

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Identification and Control of an Oxygen Provider System for a Biological Capsule

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Abstract

Providing oxygen is a necessary process in manned missions to space. The aim of this paper is to identify the dynamics of an open loop control system in preparation for feature missions. A linear time invariant model is identified with data gathered from pre-flight tests of Kavoshgar, the Iranian bio-capsule. Numerical evaluation of the resulting model and its validation are given. The resulting time discrete model is used to drive the optimal setting that minimizes power consumption of the system.

Keywords: System Identification, Control, Parameter Estimation, Power minimization, Linear Time Invariant Systems.

1. Introduction

Reduction of CO_2 and providing oxygen is one of the most important considerations in a manned flight to outer space. Controlling the levels of gases in a closed, sealed area with limitations of weight, power, and volume, and their impact on the health of the crew, define our special technical and operational requirements. In addition to transferring oxygen with bio capsules from earth, there are oxygen releasing systems based on the electrolysis of silicate melt O. R. Colson, L. A. Haskin (1993), the photosynthetic gas exchanger J. H. Bates (1961), the carbothermal process A. H. Cutler, P. A. Krag (1985), and oxygen-organic materials C. M. Kaoa, S. C. Chen, M. C. Suc (2001).
To provide the required oxygen, and eliminate CO_2 exhaled by the monkey,

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an oxygen provider system (OPS) was designed for Kavoshgar, which is a manned space vehicle carrying a rhesus monkey into suborbital flight. This gas-controlling system works based on chemical reactions. In past missions, the oxygen provider was powered on continuously for the entire 5-hour mission for safety and to avoid hypoxia. Owing to previous success and increased levels of technological readiness, there is interest in being able to control the oxygen levels by powering the system on and off during the mission, and during special situations. This will result in a reduction of power consumption, weight, cost of materials, and provide better living conditions.

In order to design such a controller, the dynamics of the system are required as the first step. The impact of the on/off switching on the current and feature levels of gases has to be known. This motivates our system identification approach to be able to estimate the system behavior via experimental data gathered during integration and final tests.

For some of the recent application of system identification, for example J. Zhang, Y. Wei, H. Qi (2016) may be addressed, where, a recursive least-squares algorithm was used for online parameter identification and estimation of the amount of charge in lithium iron phosphate batteries. In R. Delpoux, T. Floquet (2015), an algebraic online parameter-estimation method was proposed and applied to a permanent magnet stepper motor. A new class of nonlinear fractional models based on the Volterra series was proposed by A. Maachoua, et.al. (2014) for modelling nonlinear diffusive phenomena in order to estimate thermal parameters in cases where the temperature variations are large. In C. Wang (2015), a fast affine projection technique was applied for system identification of a DC–DC convertor in order to drive a novel adaptive control technique for the output voltage regulation of the convertor, and to improve its dynamic response.

In the present work, a linear time variant model is determined to simulate the system response. The resulting system is marginally stable, and simulations show reasonable accuracy of the model. The model is also evaluated and validated with data sets.

Finally, the optimal control of the resulting time discrete system is studied. The problem of optimal control leads to solving a linear programming problem with binary variables. Examining the optimal solution in test cases confirms the desired reduction in power consumption.

Figure 1: Biological capsule.

2. System Description

One of the most important aspects of space missions for Kavoshgar is to investigate biological treatments and to develop life support systems for future projects. For this purpose, a biological capsule was designed to accommodate a rhesus monkey (Figure 1). This module contained life support equipment such as monitoring vital signals, isolation, seat, and an OPS.

Obviously, any living being onboard the spacecraft consumes oxygen and produces CO_2. For a 4 kg rhesus monkey, according to G. H. Bourne (1975), the rate of oxygen consumption is 51.7 ± 10.3 ml/min. In our test case, the CO_2 concentration when the monkey is in the biological capsule with closed doors grows from 400 ppm to 6000 ppm in 15 min when the oxygen provider system is off. This means that, the CO_2 production rate in an 80 liters volume of the pressurized capsule is 29.86 ml/min. According to R. Rising, J. Lin (2013), the respiratory quotient of the rhesus monkey in a unstressed situation is 0.75. Then, the oxygen consumption rate for the monkey in the experimental test is 39.81 ml/min, which is in the theoretical range.

The aforementioned calculations show that a monkey consumes oxygen in its closed area at a rate of about 40 ml per minute. Remembering the 5 hours total mission time, 72 liters of oxygen is needed, which is impossible to include from the mission onset: the capacity of the bio-capsule is 80 l, where the maximum fraction of initial oxygen can only be 25% of the total volume. This shows the existence of a system for CO_2 reduction and oxygen production is an essential requirement. To meet this requirement, a chemical reactor was developed for Kavoshgar project. It works based on the follow-

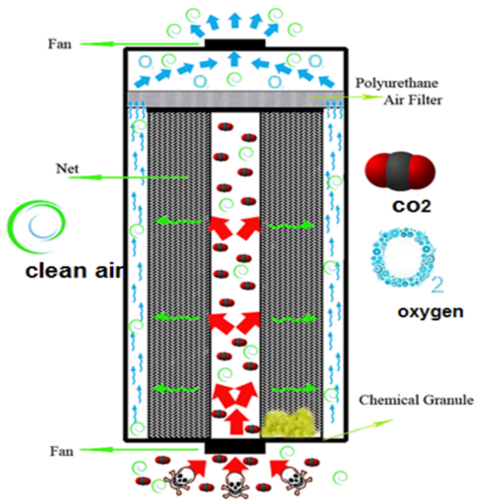

Figure 2: Schematic of the OPS (K. H. Javadi, R. Zakeri, M.R. Salimi, M. Sheyda, M. Ebrahimi (2013)).

ing chemical reaction, where sodium peroxide reacts with CO_2 to produce oxygen:

$$Na_2O_2 + CO_2 \rightarrow Na_2O_3 + \frac{1}{2}O_2 \tag{1}$$

With this reaction, the CO_2 produced by respiration reacts with Na_2O_2 to make oxygen.
As depicted in Figure 2, the system consists of three hollow cylinders. A fan in the bottom pulls air into the central cylinder. Then, air enters into the second part which is a porous medium filled with Na_2O_2 granules. The chemical reaction (1) occurs in this section, and the clean air is withdrawn by the upper fan and enters back into the bio-capsule.

3. Experimental Setup

In order to gathering data and identify the influencing factors of the capsule's environment, a series of test was performed. In these preflight tests, the monkey was in a sealed capsule similar to real flight conditions. All instruments and sensors were attached to the monkey and the capsule. Then,

Table 1: Equipment and their tasks in the experimental test

Equipment	**Task**
Biological Capsule	Providing the space for sitting the monkey, supplying the internal lighting
Oxygen Providing System	Reduction of CO2, providing oxygen for the monkey, air conditioning
Power Unit	Supplying electrical power for the operation of the OPS, lighting system and onboard data acquisition
Video Telemetry	Sending online pictures of the monkey's situation for monitoring in the ground station
Onboard Data Acquisition	Sampling and recording data from the environmental and vital sensors
Portable Metering Device	Indication environmental and vital signals such as internal pressure, temperature, humidity, CO2 and oxygen concentration
Onboard environmental sensors	Measuring the internal temperature, internal pressure(two sets), air humidity, CO2 concentration, and oxygen concentration
Vital sensors	Measuring the heart rate, skin temperature, and tympanic temperature

the onboard data gathering system was power up and recorded the environmental parameters and vital signals at a rate of one sample per minute. Data were also recorded by operators from portable metering devices in order to check the acquisition system. Table 1 shows the equipment which were used in this test.

In the first part of the sampling process, the OPS was off for the first 15 minutes and turned on for the remaining 65 minutes of the test. Data were gathered as is shown and studied in the next section. Figure 3 shows a flowchart of the test process.

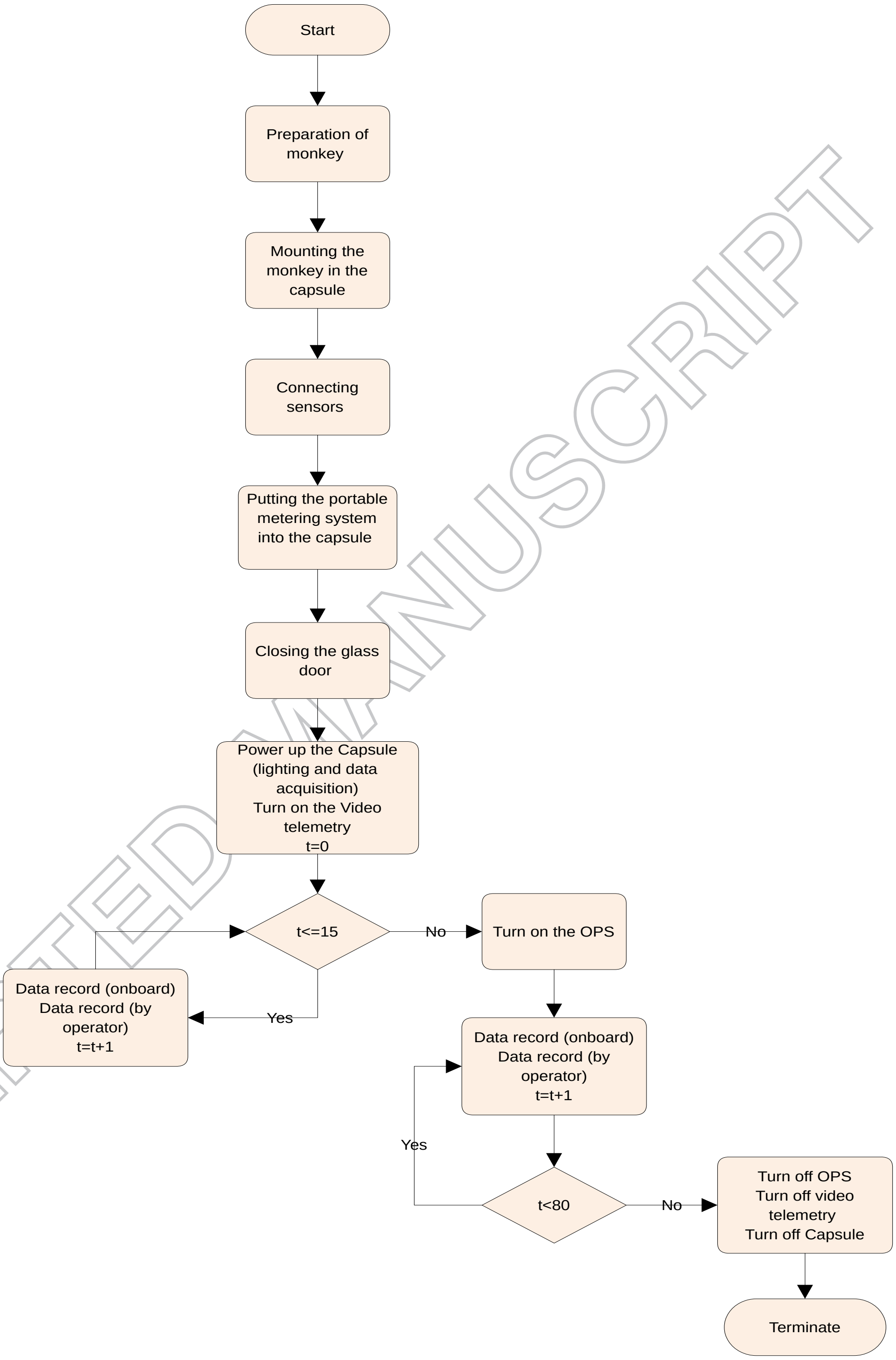

Figure 3: Flowchart of the experimental test for gathering the required data.

4. Environmental Factors

In past missions, the system is powered on 30 minutes before launch up to the end of the mission (5 hours). Test results show that the system it is not necessary working, and hence turned on, over the entire duration of the mission; indeed it may be powered on and off in special circumstances. In order to find such time points, knowledge of the dynamics and characteristics of the system is required. The important environmental parameters are listed subsequently.

4.1. oxygen

A correctly operating OPS increases the percentage of oxygen in the bio-capsule. In a functional system test with a monkey in its seat and with closed doors, the OPS is first turned off for 15 minutes, whereby it is turned on to measure the amount oxygen and CO_2 changes. During this test, data from onboard sensors was recorded every minute as shown in Figure 4. In the first part, i.e. without oxygen production, the oxygen levels decreased from 22% to 21% because of the monkey's breathing. After turning on the OPS, oxygen was produced and its percentage increased up to 25% at the end of the first hour of OPS operation. As oxygen levels over 25% are harmful for the creature, is it necessary to power off the OPS at some time based on knowledge of the system's dynamics, which will be determined via system identification.

4.2. Carbon Dioxide

In the aforementioned experimental test, the amount of CO_2 was also measured, see Figure 5. As can be seen, up to the 15th minute of the test, i.e. when the OPS was turned off, the density of CO_2 increased due to the animals breathing. When oxygen production started, the amount of CO_2 decreased based on reaction (1). In a 1-hour test, the CO_2 amount decreased from 4500 ppm to 380 ppm.

4.3. Temperature

The reaction (1) is exothermic and adds heat to the bio-capsule. As is shown in Figure 6, during a 80-min mission, the temperature increased from 29°C to 35.5°C. Therefore, based on the linear behavior of temperature, for a full mission, an increase of about 24°C is expected, which may be harmful for the monkey when the oxygen provider is working all the time and when

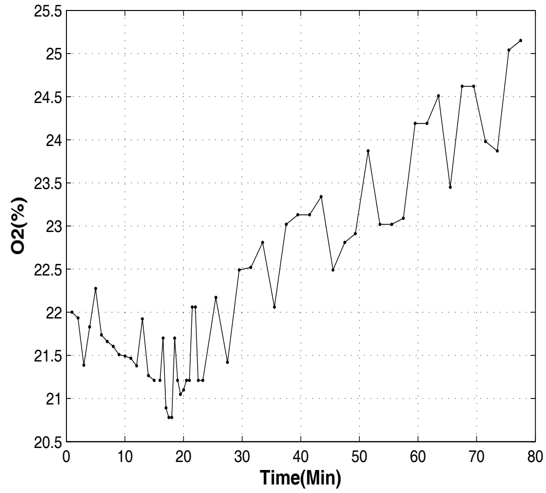

Figure 4: Oxygen percentage in the bio-capsule.

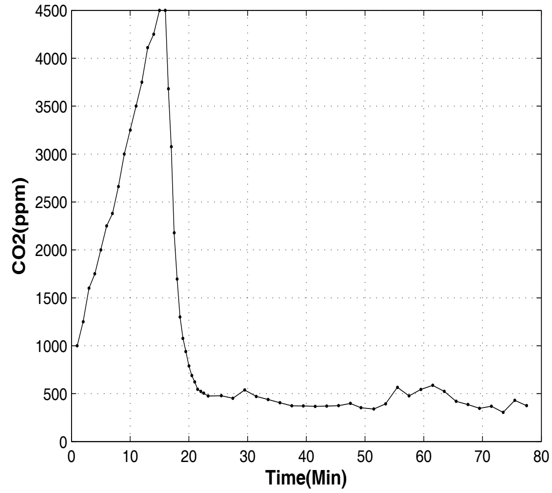

Figure 5: Carbon dioxide density in the bio-capsule.

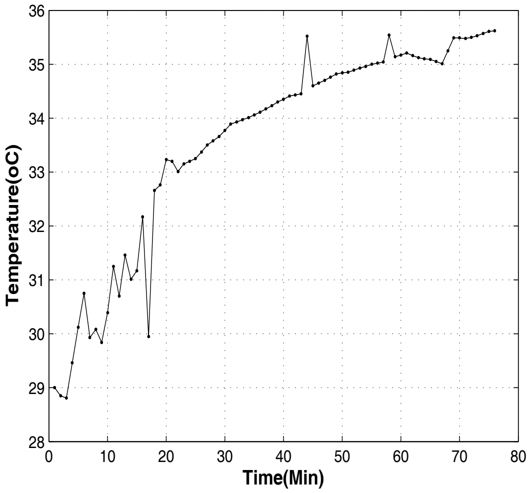

Figure 6: Internal temperature in the bio-capsule.

finding the payload takes a long time.
It should be noted that there are other heat sources, such as the monkey itself, electrical equipment in the capsule, and lighting. However, the quota of the oxygen provider is considerable, and designers are interested in identifying the relationship between the temperature changes caused by the OPS and other parameters via the experimental data used in this paper.

4.4. Pressure

Internal pressure of the bio-capsule is another key parameter affected by the operating OPS. As shown in Figure 7, the process of converting CO_2 to oxygen increases the internal pressure. In our test case, the pressure grew from 920 millibar to 936 millibar in 16 minutes. This shows that the pressure increases 1 millibar per minute when the OPS is working continuously.

4.5. Humidity

The exothermic behavior of reaction (1) causes a reduction of humidity in the bio-capsule, while the respiration of the monkey increases it. However, the drying attributed to the oxygen provider overcomes the effect of respiration to the overall humidity. Figure 8 shows the percentage of humidity in an experimental test. In this test, the oxygen provider system was powered off from begin up to 15 minutes, then it was powered on for 1 hour. Results show

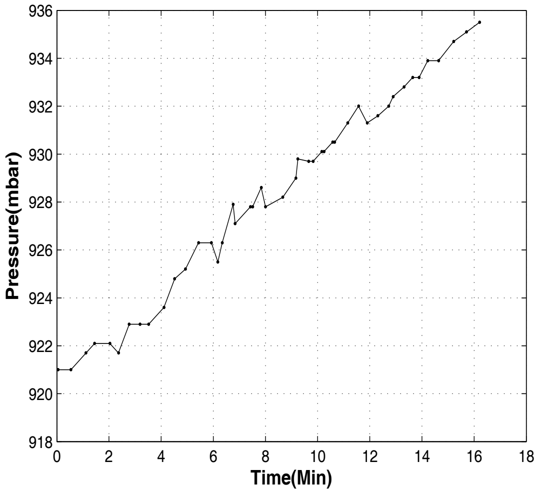

Figure 7: Internal pressure of the bio-capsule.

that the humidity increased from 21% to 34% when the OPS was switched off. This increase was due to the respiration of the animal. When the OPS was powered on, the humidity decreased as expected, from 33% to 8%. During this phase, the dominancy of the OSP to the monkey respiration towards air-drying is proved. It is clear that when the mission takes a long time, the humidity in the bio-capsule drops. It should be noted that humidity is also influenced by temperature, the amount of CO_2 and oxygen in the air, and the internal pressure.

4.6. Correlations

A quick view of the aforementioned graphs (Figures 4-8) indicates that there are some relationships and dependencies between the related parameters. The internal temperature and pressure, for example, seem to increase at the same rate. Humidity and CO_2 both decrease, and it seems that they are correlated with each other. To illustrate the quantitative measure of such dependencies, one may use the cross correlation coefficient between each pairs of experimental data, which is defined as:

$$R(x, y) = \frac{\sum_{i=0}^{N}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=0}^{N}(x_i - \bar{x})^2 \sum_{i=0}^{N}(y_i - \bar{y})^2}} \tag{2}$$

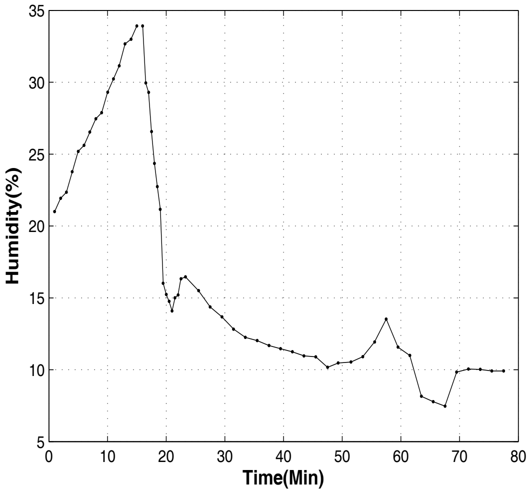

Figure 8: Humidity levels in the bio-capsule.

where $\bar{x}$ stands for the average of x. The cross correlation coefficient ranges from -1.0 to +1.0. A value of -1.0 indicates a perfect negative correlation, while a correlation of 1.0 indicates a perfect positive correlation. Some of the cross correlation for the related data were calculated, for example:
R(oxygen,CO_2)=-0.55
R(oxygen,Humidity)=-0.71
R(oxygen,Temperature)=0.70
R(CO_2,Humidity)=0.95
R(CO_2,Temperature)=-0.67
R(Humidity,Temperature)=-0.82

This shows that, for the above example, the CO_2 density and humidity percentage are highly correlated with each other, while the humidity and temperature are negatively correlated with each other. This shows the dependency of these quantities within the closed environment of the bio-capsule. A mathematical model that describes hidden relations in this system via mathematical expressions is presented in the next section.

5. System Identification

As mentioned previously, a system identification method was used to describe the dynamics of the OPS as mathematical relations. First, the

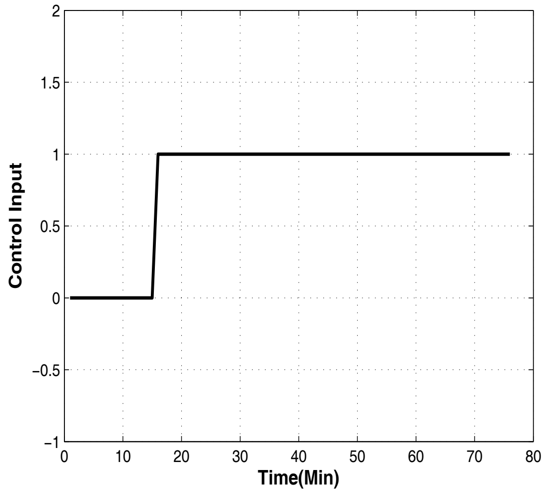

Figure 9: Input signal used in the identification process.

input and output signals are defined. Let us assume that $u(t)$ is the on-off situation of the OPS at time t, which is considered as the input of the system. It is a Bang-Bang control with 0–1 values as:

$$u(t) = \begin{cases} 1 & \text{if the OPS is on at time } t, \\ 0 & \text{if the OPS is off at time } t. \end{cases} \tag{3}$$

There are five components of the output vector:

$$y(t) = (y_1(t), y_2(t), y_3(t), y_4(t), y_5(t))^T \tag{4}$$

as follows:
$y_1(t)$ = Percentage of oxygen in the capsule
$y_2(t)$ = Carbon dioxide density in the capsule (ppm)
$y_3(t)$ = Percentage of humidity in the capsule
$y_4(t)$ = Temperature in the capsule (°C)
$y_5(t)$ = Internal pressure in the capsule (millibar)

For the model set, let us consider a set of discrete time invariant linear state space systems as:

$$x(t+1) = Ax(t) + Bu(t) \tag{5}$$
$$y(t) = Cx(t) + Du(t) \tag{6}$$

With a degree of 5, there are 60 unknown coefficients in matrices A, B, C, and D which have to be determined in such a way that the resulting system estimate matches the experimental data. Data was gathered when the OPS was off for 15 minutes, and then turned on for 60 minutes. As such, the response of the system to a step input, as in Figure 9, is available for identification. The parameter estimation method (L. Ljung (1999)) was used to find the model parameters. It is assumed that vector Z shows all experimental data, and θ shows all unknown parameters. The related error of an individual parameter θ is defined as:

$$\varepsilon(t,\theta) = y(t) - \hat{y}(t), \tag{7}$$

where $y(t)$ is the experimental value, and $\hat{y}(t)$ is its related estimation. In the case of this research, a set of data gathered during an experimental preflight test for $N = 80$ minutes was used. The sampling rate was one sample per minute. In addition to recording the sensor data with the data acquisition system, samples were checked with an analogue thermometer, barometer and CO_2 indicator. Therefore, with 80 samples in each of the five channels in (4), the vector $Z = [y(t_0), y(t_1), \cdots, y(t_{79})]$ is ready. Then, the vector of parameters θ^* has to be determined in such a way that $\varepsilon(t_i, \theta)$ in (7) is zero for all samples. However, with 60 unknown parameters and 80 equations, this is an over-determined linear system. An efficient method for solving such a system is to use the least-squares method in which the following average norm of errors has to be minimized:

$$V_N(\theta, Z) = \frac{1}{N}\sum_{i=1}^{N}(\varepsilon(t_i,\theta))^2. \tag{8}$$

The total error function of (8) was minimized by using the least-squares method proposed in M. H. Farahi, H. Fahimian, A. R. Nazemi (2008). The matrix coefficients were found as:

$$A = \begin{bmatrix} 0.5089 & 0.2913 & -0.2753 & -0.0322 & 0.1015 \\ -0.0048 & 0.9675 & -0.0843 & -0.0213 & -0.0178 \\ -1.1719 & -0.2220 & 0.7467 & -0.0389 & 0.0415 \\ 0.1790 & 0.2837 & -0.0181 & 0.7921 & 0.3327 \\ 0.06241 & -0.2489 & -1.003 & -0.3743 & 0.9305 \end{bmatrix}$$

$$B = \begin{bmatrix} -0.8966 & -0.6064 & -0.3525 & -0.2185 & -0.7204 \end{bmatrix}^T$$

$$C = \begin{bmatrix} -1.888 & 51.69 & 0.3654 & 2.468 & -3.865 \\ 3154 & 3505 & -1191 & 6.615 & -606.8 \\ 20.61 & 45.30 & -8.38 & 0.3182 & -7.399 \\ -2.048 & 70.38 & -2.07 & 3.22 & -4.921 \\ -24.77 & 2131 & -29.46 & 91.96 & -166.4 \end{bmatrix}$$

$$D = \begin{bmatrix} 0 & 250 & 0 & 0 & -7 \end{bmatrix}^T$$

5.1. Stability

To study the stability properties of the resulting linear time invariant system, the magnitude of the eigenvalues of matrix A were calculated, and found to be 1.0001, 0.9241, 0.8231, 0.8231, 0.5120. Since these eigenvalues are in the unit circle or on its boundary, the system is marginally stable(T. Boom (2006)). This means that if an impulse of finite magnitude is given as input, then the system will not give an unbounded output, but neither will the output return to zero.

5.2. Validation

To check the validity of our results, the estimation was calculated by using the input signal of the experiment and comparing the estimated and actual data. To start the simulation, initial parameter values are needed. From the experimental data, $y(0) = (22, 1000, 21, 29, 920)^T$. Therefore, the related initial value for the state vector was calculated as:

$$x(0) = C^{-1}(y(0) - Du(0)) = \begin{bmatrix} -0.1674 \\ 0.5431 \\ 0.4492 \\ -3.7682 \\ -0.7110 \end{bmatrix}$$

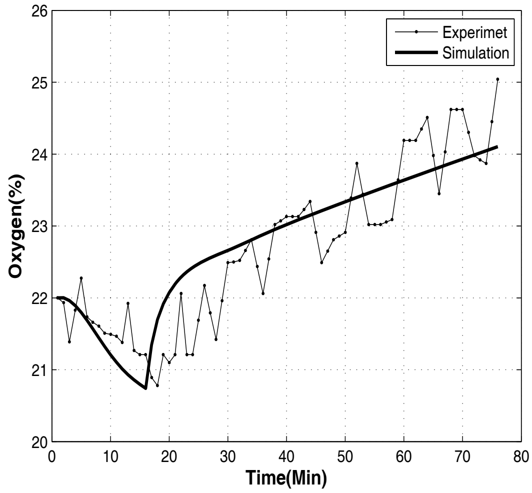

Figure 10: Experimental and simulated data oxygen percentages.

In Figure 10, the simulated oxygen percentage is shown. It is clear that the simulated output of the resulting system tracks the data well.
A similar graph of the CO_2 density is also depicted in Figure 11. The simulation coincides with the experimental data for the first 20 minutes, and after that an acceptable trend is observed.

Figure 12 shows the experimental and estimated humidity in the capsule. As can be seen, the founded model estimates this quantity well.

The model also estimated the temperature and pressure, as can be seen in Figure 13 and Figure 14. For the final course of pressure, the model overestimates the pressure by 15%, but still maintains the general trend, which has an acceptable accuracy.

6. Optimal Control

The system response to the two possible step functions $u = 0$ and $u = 1$ were obtained as depicted in Figure 15. When the OPS was off, the CO_2 level reached and stayed at 6000 ppm, which coincides well with the experimental results.
The aim of the optimal control was to keep the gases and environmental levels at a desired level while minimizing the power usage by switching the OPS on and off.

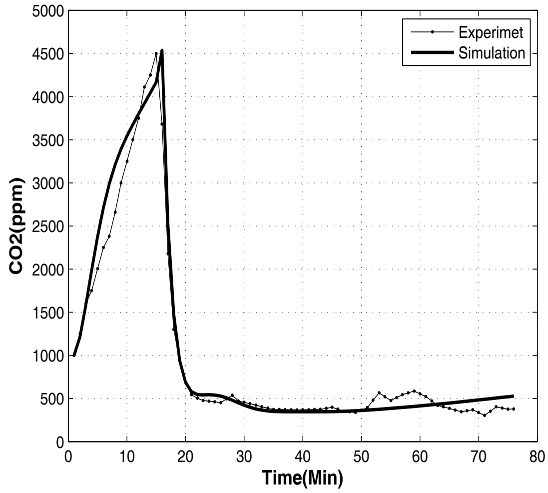

Figure 11: Experimental and simulated CO_2 densities.

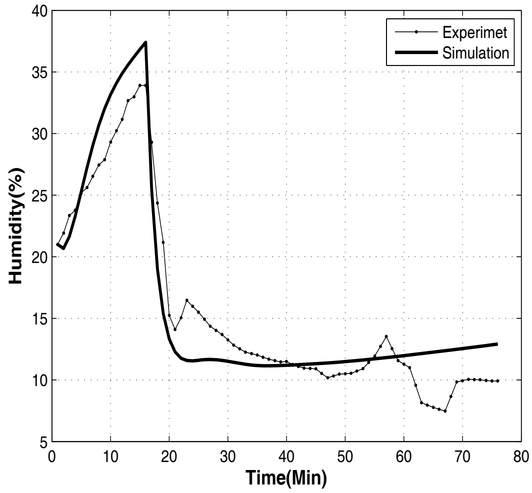

Figure 12: Experimental and simulated humidity levels.

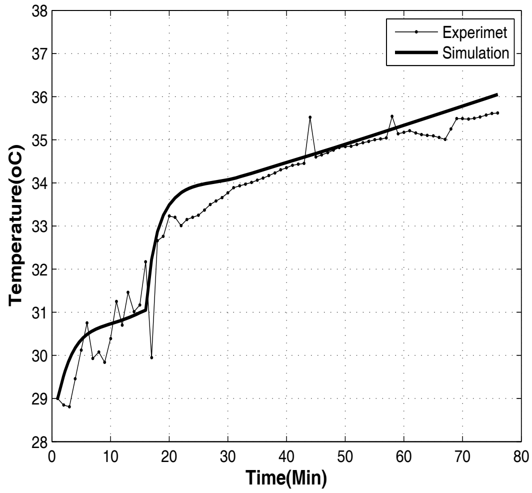

Figure 13: Experimental and simulated temperature.

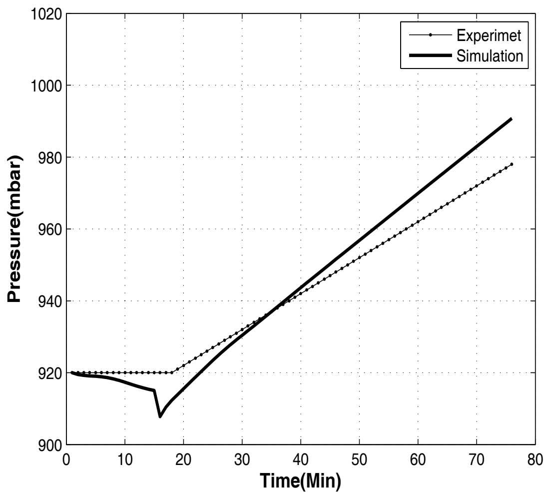

Figure 14: Experimental and simulated pressure.

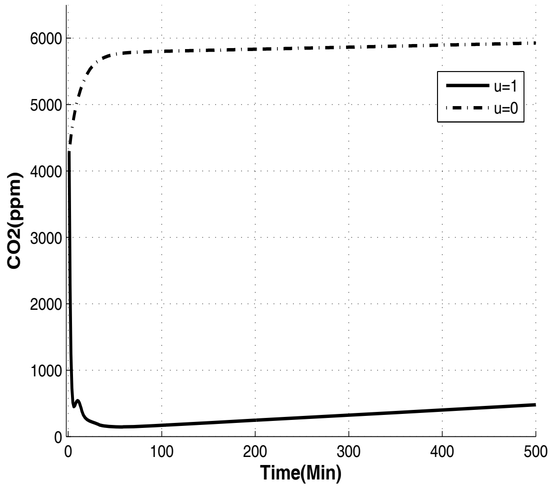

Figure 15: System responses to $u(t) = 0$ and $u(t) = 1$.

It is to be noted that open loop control is preferred to closed loop control because the latter needs to measure the level of gases and environmental factors, where, low reliable sensors, will affect the control loop.
With regards the problem of power and energy minimization, the objective usually has a quadratic form. However, in the present case, as the control values are binary $u(t) \in \{0, 1\}$, the quadratic form is equivalent to the linear one. Therefore, the objective function here is considered as a weighed summation of the control values, as follows, in discrete form, which is to be minimized:

$$\sum_{t=0}^{N} r(t)u(t). \tag{9}$$

Here, $r(t), t = 0, 1, 2, \ldots, N$ are positive weights. There are also possible constraints on the responses:

$$y_{min} \leq y(t) \leq y_{max}, \tag{10}$$

where y_{min} and y_{max} are vectors of the lower and upper limits on the responses of system (5)-(6), respectively. Given an initial value of $x(0) = x_0$, using a procedure similar to the one presented in G. C. Goodwin, M. M.

Seron, J. A. de Doná (2005), and including equation (5), the state vector $x_t = x(t)$ which is related to the unknown input $u_t = t(u)$ is obtained as:

$$\begin{aligned} x_1 &= Ax_0 + Bu_0, \\ x_2 &= A^2x_0 + ABu_0 + Bu_1, \\ &\vdots \\ x_N &= A^Nx_0 + A^{N-1}Bu_0 + \cdots + Bu_{N-1}. \end{aligned} \tag{11}$$

The aforementioned equation may be written in matrix form as follows:

$$\mathbf{x} = \Gamma\mathbf{u} + \Omega x_0, \tag{12}$$

where,

$$\Gamma = \begin{bmatrix} B & 0 & \cdots & 0 \\ AB & B & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots \\ A^{N-1}B & A^{N-2}B & \cdots & B \end{bmatrix}, \Omega = \begin{bmatrix} A \\ A^2 \\ \vdots \\ A^N \end{bmatrix}, \mathbf{x} = \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_N \end{bmatrix}, \mathbf{u} = \begin{bmatrix} u_0 \\ u_1 \\ \vdots \\ u_{N-1} \end{bmatrix}.$$

Therefore, from (6) and (12), the vector of the system's responses is calculated as:

$$\mathbf{y} = (C\Gamma + \mathrm{diag}(D))\mathbf{u} + C\Omega x_0, \tag{13}$$

where diag(D) is a block diagonal matrix with D as its diagonal entries, and multiplication of C to Γ and Ω is performed in a component-wise manner. The constraints may also be written as:

$$\mathbf{y} \leq y_{max}, \quad -\mathbf{y} \leq -y_{min}. \tag{14}$$

Now, merging (13) and (14) results in:

$$L\mathbf{u} \leq W, \tag{15}$$

where,

$$Ł = \begin{bmatrix} (C\Gamma + \mathrm{diag}(D)) \\ -(C\Gamma + \mathrm{diag}(D)) \end{bmatrix}_{10N\times N}, W = \begin{bmatrix} y_{max} - C\Omega x_0 \\ -y_{min} + C\Omega x_0 \end{bmatrix}_{10N\times 1}.$$

Therefore, the problem of optimally controlling the power consumption is reduced to the following integer linear programming problem with $10N$ constraints:

Table 2: Best-fitting parameter values

	Oxygen	**CO_2**	**Humidity**	**Temperature**	**Pressure**
min	19	500	5	28	870
max	22	1000,2000,4000	42	33	905
initial value	22	1000	16	29	880

$$\begin{aligned} &\min \ \mathbf{r}.\mathbf{u} \\ &\text{s.t.} \\ &\quad L\mathbf{u} \leq W \\ &\quad \mathbf{u} \in \{0,1\} \end{aligned} \tag{16}$$

where $\mathbf{r} = [r(0), r(1), \cdots r(N-1)]$. The only decision variable in this linear programming problem is vector $\mathbf{u}$ with N components. After solving this problem, the optimal control will be found.

The problem was solved with the branch-and-bound algorithm in $N = 100$ minutes, $r(t) = 1, t = 0, 1, \cdots, N$, and a set of parameters as shown in Table 2. In the first simulation, the upper bound for CO2 is 4000, the optimal objective function is 8 which is 92% lower than the case when the OPS is working continuously during this time period.

Figure 16 shows the control function, and the system responses to it including CO2 and oxygen levels and temperature. As it can be seen, the resulting optimal control has an off-on-off form with 16 switches between the on and off positions.

In the second case, the upper bound for CO2 is set to 3000 ppm, therefore, more working periods of OPS was expected to keep the CO2 level below 3000 ppm with respect to the first case.

As depicted in Figure 17, the control function has more switches. The optimal objective, as expected, increases to 36 which is 42% lower that full working of OPS. This means that when using the resulting control function, the power consumption reduces by 42% while the CO2 level does not grow over 3000 ppm.

In the third run, the upper bound of CO2 was set to 2000 ppm. The results are shown in Figure 18. The objective reduced to 51 with 100 switches.

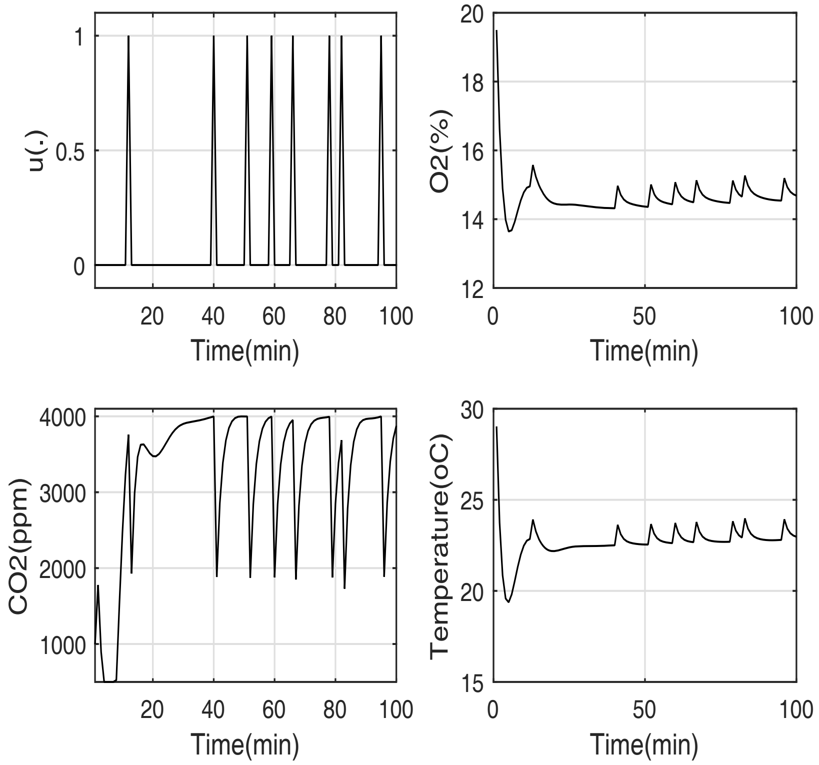

Figure 16: The optimal control and system responses for a CO2 upper bound of 4000 ppm.

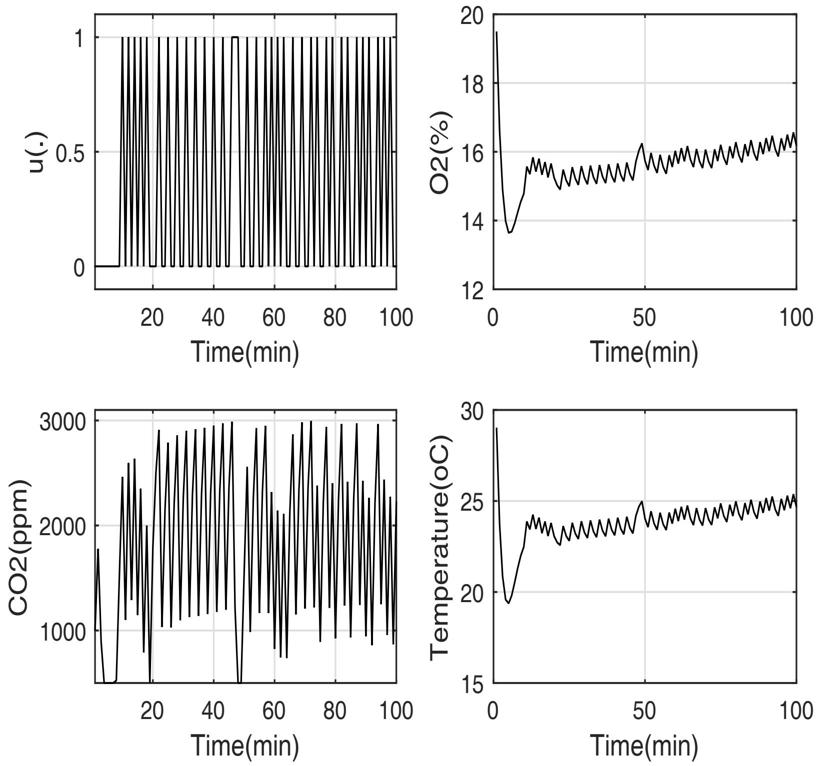

Figure 17: The optimal control and system responses for a CO2 upper bound of 3000 ppm.

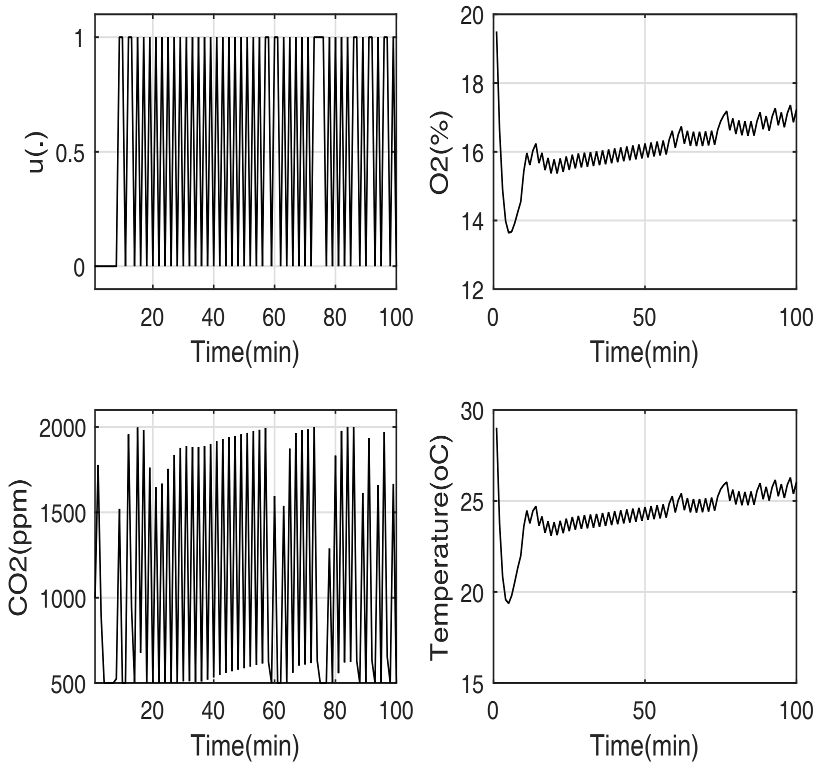

Figure 18: The optimal control and system responses for a CO2 upper bound of 2000 ppm.

6.1. Averaging Approach

When solving (16), it was seen that the control function has many switches, especially when the CO2 upper bound decreased. In cases such as a sequence turning on and off what is undesirable, the averaging approach may be applied. In this case, the upper bound on each element of $\mathbf{y}$ is set to the relating average. For example, for CO2, the present constraints in (10) are

$$y_{min} \leq y_2(t) \leq y_{max}, t = 1, 2, \cdots, N. \tag{17}$$

However in averaging approach, they read as

$$y_{min} \leq \overline{y}_2 \leq y_{max}, t = 1, 2, \cdots, N, \tag{18}$$

where,

$$\overline{y}_2 = \frac{1}{N} \sum_{t=1}^{N} y_2(t). \tag{19}$$

Therefore, the linear programming problem (16) is changed to an averaged form as follows:

$$\begin{aligned} &\min \quad \mathbf{r}.\mathbf{u} \\ &\text{s.t.} \\ &\quad \overline{L}\mathbf{u} \leq \overline{W} \\ &\quad \mathbf{u} \in \{0, 1\} \end{aligned} \tag{20}$$

Here the number of constraints was reduced to five, and each of them is related to one of the parameters of Table 2.
The problem (20) was also solved for the same values used in the non-averaged method. The results for a CO2 upper bound of 2000 ppm are shown in Figure 19, for example. It is clear that the control function does not have the same fluctuations as seen in Figure 18 and there are only two switches, while the average CO2 level remained below the upper bound. In order to compare the averaged and non-averaged approaches, in Table 3 the solution parameters are compared. The second column shows the upper bound of CO2, while the third column shows the wall clock time (WCT) that measures the running time for solving the related LP problem. As is expected, because of the reduction in the number of constraints in (20), solving the averaged problem is very fast with respect to the non-averaged method. The number of switches is also reduced to two in all three cases. The objective

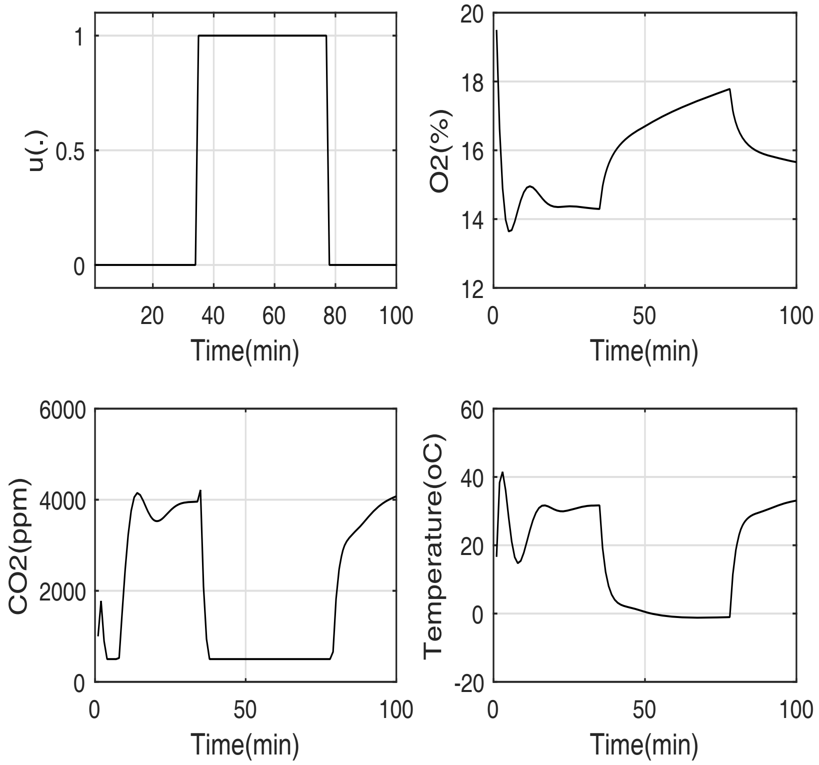

Figure 19: The optimal control and system responses of the for a CO2 upper bound of 2000 ppm (average).

function and power consumption is also better than in the non-average case. The last column shows the improvement in power consumption with respect to the case of a fully operating OPS.
It should be noted that the solution of the averaged approach will violate the upper and lower bound, but remains in the region in an average meaning.

7. Conclusion

A linear time invariant model was obtained to describe the governing dynamics of an OPS for a space bio-capsule. Our chosen parameter estimation method was based on system identification theory. The resulting model was

Table 3: Comparison of results

Method	**CO_2 bound**	**WCT(sec)**	**Switches**	**Objective**	**Improvment**
Non-average	4000	221.86	16	8	92%
Non-average	3000	2234.27	32	36	64%
Non-average	2000	2762.68	100	51	49%
Average	4000	0.34	2	2	98%
Average	3000	0.34	2	16	76%
Average	2000	0.33	2	43	57%

also validated via experimental data. Finally, the model was used to design an open loop controller. Simulations show that with the obtained optimal control, the desired environmental conditions are preserved and electrical power consumption is reduced.

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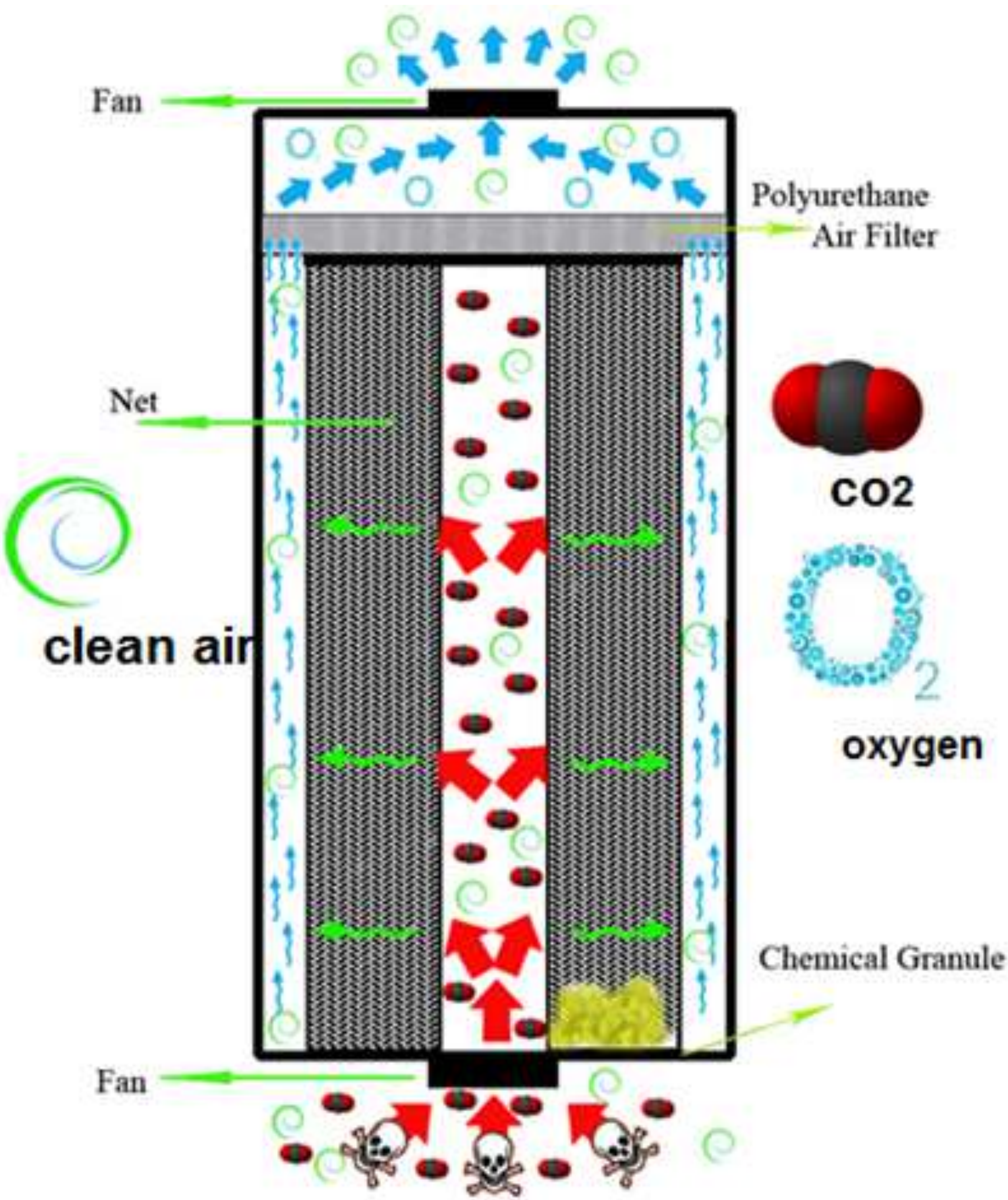
Fan
Polyurethane
Air Filter
Net
CO2
clean air
oxygen
Chemical Granule
Fan

Author Bio

Seyed Hamed Hashemi Mehne was born in Mashhad, Iran, 1978. He received B.Sc., M.Sc. and Ph.D. degrees from Fredowsi University of Mashhad, all in Applied Mathematics, in 1999, 2001, and 2005, respectively. Currently, he is an assistant professor at the Aerospace Research Institute (Tehran, Iran). His research interests are optimal control, numerical mathematics, shape optimization and parallel computing.

This research is the first attempt to find a mathematical model for an oxygen provider system in a biological capsule. By using experimental data and methods of system identification, the relations between different environmental parameters of the capsule were formulated as a valid discrete linear dynamical system. Optimal control for minimizing the electrical power consumption was also studied. The results and methods may be used to increase the level of automation of the next generation of the biological capsules.

Responses to Reviewers' Comments

First, I appreciate the reviewers for valuable comments, which help me improving my work in the revised format.

Reviewer 1: Still the experimental part of the paper is not very clear. Is is possible to give a diagram of the overall experimental setup. The author needs to provide the results of the experiments which remained uncompleted. I would suggest the author also to provide a list of instruments used in tabular form. If possible a flowchart of the experimental process can be included to enrich the content of the paper which will also help the readers to understand the methodology.
Answer: A new section was added in pages 4-6 regarding the test setup in details.

Reviewer 1: I would suggest the author not to use "WE". Like in place of "We identified a linear time invariant model with data gathered from pre-flight tests of Kavoshgar, the Iranian bio-capsule. " it must be "A linear time invariant model with data gathered from pre-flight tests of Kavoshgar, the Iranian bio-capsule is being identified in this paper.". Moreover when there is only one author how can we word be used. Except that there are some English language problem which needs to be identified and corrected properly.
Reviewer 1: Again "Our" word is being used in the conclusion. Moreover in the conclusion the author must clearly show how their proposed topology is better then the other.
Reviewer 1: The is a need to improve the quality of the manuscript in terms of english language as i mentioned before.
Answer: The paper in the new version has been corrected. For grammatical problems, it has been corrected by an international language editing service.

References – optional feedback
Reviewer 1: The author must include some more reference of the OPS systems.
Answer: New references on OPS systems were added.

Reviewer 2: More focus needs to be given on the control part of the paper, or modify the title "Identification of the Oxygen Providing System for a Biological Capsule".
Answer: In the revised paper, the control part has been reinforced and two average and non-average approach were presented and compared.

Reviewer 2: Some experiment tests need to be supplied complete.
Answer: A new section is added in pages 4-6 regarding the test setup in details.