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A Smart Oxygen Supply Control System Based On MEMS Capacitive Pressure Sensors

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Abstract

A new smart oxygen control system (SOCS) that regulates the oxygen supply to patients is presented in this paper. The system is designed for patient smart oxygen delivery in hospitals. The operation is based on MEMS Pressure Sensors and its scope is to minimize the losses of oxygen during in-hospital use as well as monitoring the oxygen consumption. Dedicated CMOS electronics are used to perform sensor signal conditioning and calibration. It is autonomous using Li-Po battery and it is wireless connected with mobile devices and an IoT platform Experimental results are also provided.

1. Introduction

Oxygen is considered a medicine and therefore is often used for the recovery of patients in various health facilities. The supply of oxygen in hospitals is distributed in each patient through the medical gases network in gaseous form. The oxygen consumption in hospitals is extremely high on a global scale. Oxygen is used through special devices that regulate its flow and depending on the age, physique and condition of the patient, the required volume is released at the appropriate rate. It has been ascertained that more than 25% of the average oxygen consumption in a hospital comes either from the negligence of the nursing staff, or from the inability of the patients to use these devices correctly. Therefore, it is very often observed incorrect use both in duration and quantity of oxygen. The main problem is the failure of O2 supply interruption at the appropriate time.

The system presented ensures the saving of energy and the reduction of oxygen consumption, actions that entail the direct saving of resources. It is an innovative system that does not currently exist on the global market. More specifically, the implementation of the device will solve vital problems such us, the incorrect and incomplete treatment plans, the on time oxygen supply interruption after the end of the treatment and will contribute to the reduction of cost. Additionally, the part of the device that comes into contact with the patient must be sterilized after every use to avoid hospital-acquired infections. The new system incorporates the necessary subsystem to perform the sterilization on time.

2. Device Description

2.1 SOCS Architecture and Functionalities

The SOCS is an innovative device that can control and regulate the oxygen flow supply to patients. The architecture of the system is depicted in Fig. 1.

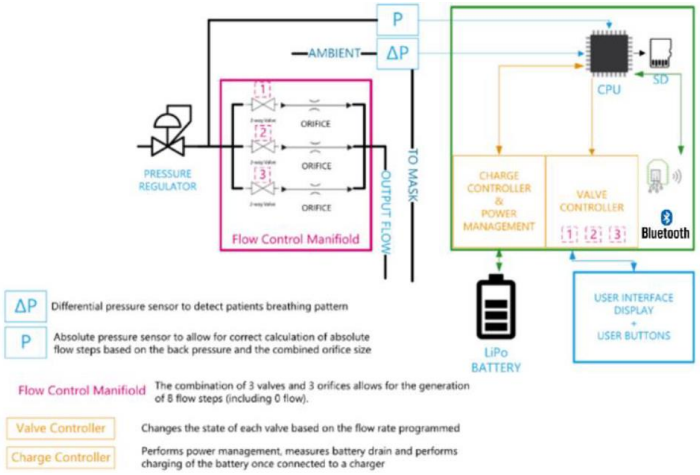

Figure 1: The complete system architecture.

The pneumatic subsystem contains two pressure sensors and three electromagnetic solenoid microvalves. The first pressure sensor is an absolute pressure sensor 5 bar range which measures the system inlet pressure connected in the inlet port (1)as shown in Fig. 2. This sensor indicates if there is oxygen supply in the system at the required pressure. The output flow will be calculated based on the inlet pressure measurement and the diameter of the flow path selected towards the outlet port(2)using the solenoid microvalves shown in Fig. 2. The second sensor is a differential pressure sensor 10 bar range with a resolution of 100 μbar. This sensor controls the oxygen supply to the patient. The breathing feedback measured through the breathing feedback port (3) shown in Fig. 2 detects whether the patient is trying to breath. The three electromagnetic solenoid microvalves have the possibility of setting different gas supplies. Depending on the combination of the activated valves, it is possible to have 8 different supply options, including the case that they are all closed at the same time. This makes it possible to perform different oxygen therapy supply programs.

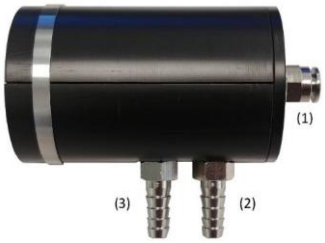

Figure 2: SOCS's exterior

The microvalves are managed from a microcontroller. The microcontroller reads all the sensors and activates or deactivates the microvalves in order to achieve the desired flow rate. Furthermore the microcontroller records and recognizes human breath presence profiles. In addition the main processor also drives the onboard LCD display following the power management profile, activating the display when it is triggered by the user or by a specific event. A Bluetooth pulse

oximeter measures the heart rate and the oxygen concentration level of the patient. Based on this the SOCS sets an alarm in case of the absence of human breathing, absence of heart beats or decreasing oxygen concentration. The microcontroller sends and receives commands from the front interface console shown in Fig. 3 and the Bluetooth interface. Mobile devices can be connected as well as a Bluetooth base stations where data are transmitted. Different operation modes can be programmed through the Bluetooth interface.

Figure 3: SOCS's Console

All data are saved in the internal (flash) memory and all alarm situations that may arise are handled from the microcontroller. Specifically, the information that are transferred and communicated to the staff of the nursing institution via Bluetooth, are: oxygen consumption, the state of the oxygen valve (open/closed), oxygen pressure (absolute/differential), alarm indication in various situations (e.g., patient respiratory arrest, loss of air pressure/leakage, low battery, etc.). The device has an embedded Li-Po battery for system autonomy which can be charged inductively at the base station.

2.2 Embedded Pressure Sensors

The basic elements of the SOCS device are the pressure sensors used to detect and control the operation as already described. The final SiP (System In Package) system contains a MEMS (Micro Electro Mechanical Systems) pressure sensor and CMOS (Complementary metal–oxide–semiconductor) integrated readout electronics with integrated logic designed and manufactured by ES Systems [1], [2]. The pressure sensor is a silicon based micromachined sensing element developed by ES Systems. Depending on its dimensions the sensor can measure in different ranges with different accuracy. ES Systems had developed a new microfabrication technology that can produce both absolute and differential silicon capacitive MEMS pressure sensors. The CMOS electronic is an ASIC (application-specific integrated circuit) specifically designed for signal conditioning and calibration of the MEMS sensor. In Fig. 4 are depicted the MEMS sensor and CMOS ASIC interconnected in the final package. The two different pressure sensors used in the SOCS are a 5 bar absolute range sensor and a 10 mbar differential range pressure sensor.

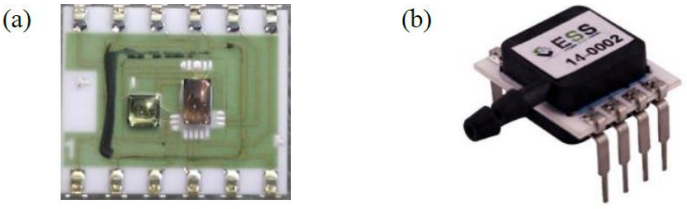

Figure 4: (a) Packaged SiP interior; (b) Packaged SiP differential pressure sensor.

3. Experimental Results

3.1 Flow control and regulation subsystem

For the calculation of the output flow the flow control and regulation subsystem relies on the absolute pressure sensor which is positioned at the pneumatic inlet of the system and on the ratio created by the combination of flow channels with different diameters. Flow channels are selected using solenoid valves. The accuracy of the calculated flow depends on the accuracy of the absolute pressure sensor. The pressure sensor used is calibrated at 5 bara and is temperature compensated between 0-60 oC. Therefore, both the accuracy of the pressure sensor and the accuracy of the calculated flow at the operating pressure and temperature conditions has been confirmed. The diagram below in Fig. 5 refers to the pressure sensor confirmation tests.

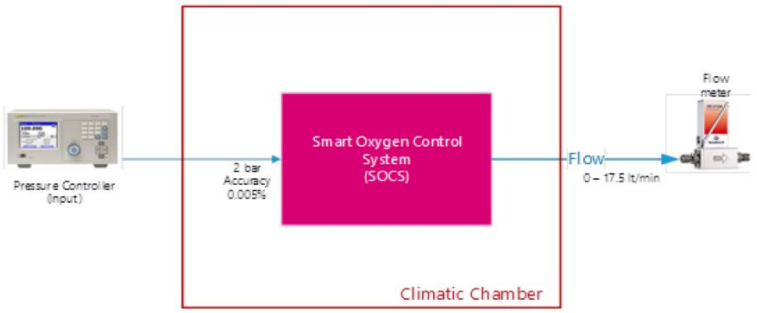

Figure 5: Absolute pressure and flow sensor test setup diagram.

The same setup was used in order to measure the output flow under the same conditions. The measurements were carried out via Low Energy Bluetooth wireless link. The flow values are summarized in Table 1.

Flow Set of SOCS (lpm)	**Corresponding Flow Out *(lpm)***
1	0
2	2.5
3	5
4	7.5
5	10
6	12.5
7	15

Table 1: Flow steps measurements.

Although the pressure in the application will be set between 2 and 2.1 bar the sensor was tested in its entire range as shown in the Fig. 6.

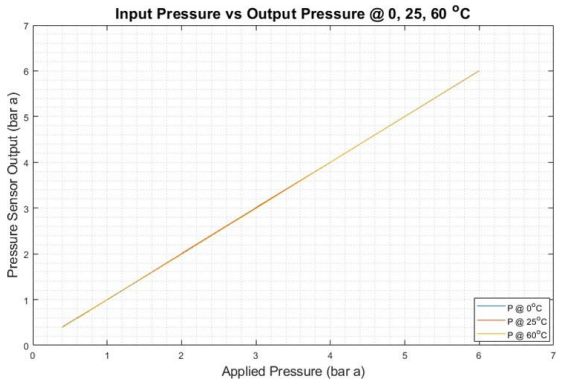

Figure 6: Diagram of pressure sensors output versus inlet applied pressure

In Fig. 7 is depicted the error of measurement compared to the reference controller value at three different temperatures. The total temperature error is measured below ± 0.015%.

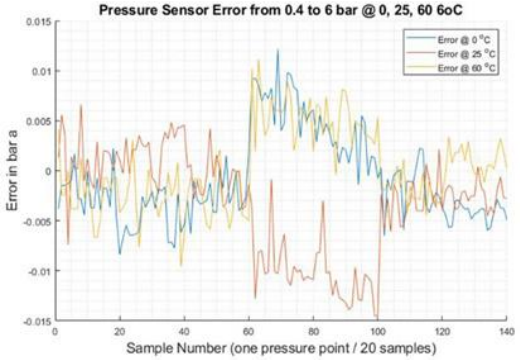

Figure 7: Inlet pressure sensor error diagram

3.2 Flow detection subsystem

The differential pressure sensor is the sensor that transmits the pressure generated by the development of vacuum during the patient's inspiratory effort. The signal pattern has been used to identify the presence of a patient in conjunction with the pulse oximeter. The sensor is calibrated on the ± 10 mbar scale and temperature compensated in the temperature range 0 – 60 oC. The following experimental setup depicted in Fig. 8 was used to validate the differential pressure sensor.

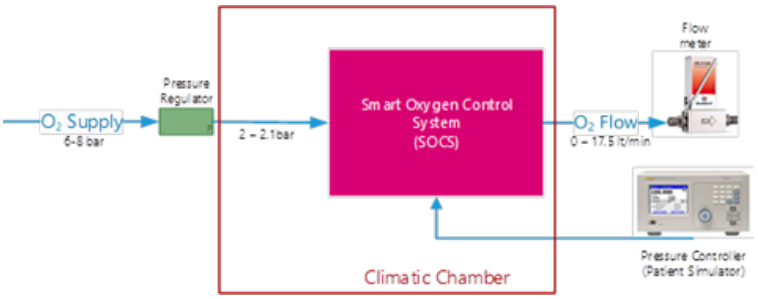

Figure 8: Experimental setup of differential pressure sensor control and patient detection algorithm

During the first experiment, the accuracy of the sensor in the compensation temperature range was checked. The sensor response was recorded at three different temperatures and compared with the calibrator reading. In Fig. 9 are depicted the measurement results.

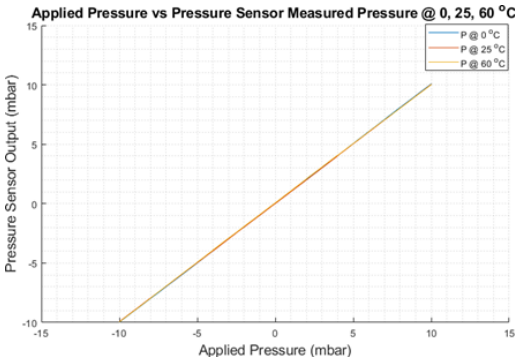

Figure 9: Pressure characterization diagram at 3 temperatures

In Fig. 10 the error between the measurement and the calibrator is depicted. The total error is below ±0.1%.

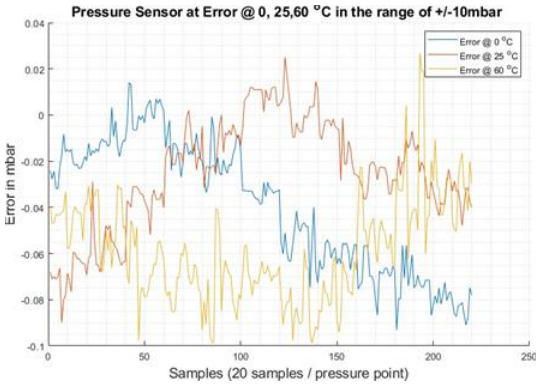

Figure 10: Plot of pressure error in the compensation temperature range

The same setup was used outside the climatic chamber, in order to check the successful detection of a breathing pattern and thus the activation of the solenoid microvalves to release the flow has been performed. The sequence of the test performed is depicted in Fig. 11. The pressure calibrator produces a specific pressure standard of ±0.5 mbar which is less than the worst case scenario depending on the patient's age and body type. After 3 breathing cycles the system activates the solenoid microvalves and releases the predetermined flow.

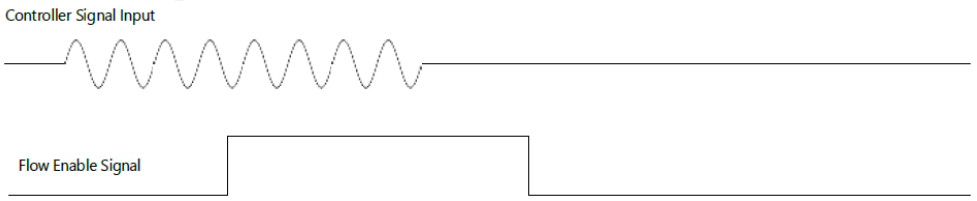

Figure 11. Test sequence diagram

The energy management systems (charge, discharge, power modes) worked flawlessly within the prescribed conditions and according to the design specifications hence allowing the device to operate on battery for 10 hours of continuous operation with a maximum charging time of 2 hours.

3.3 SOCS's operation measurement in the field

The system was measured in real conditions in order to establish the proper operation of the device and its compliance with certain specifications. These measurements were performed for each of the 7 possible device flow settings. In order to understand breathing better, the normal breathing pattern should be known. In normal breathing at rest, there are short breaths (inhalation) followed by exhalations (exhalation). Exhalation is followed by an automatic pause (or breathless period) of about 1 to 2 seconds. [3] In a sample of 50 people, the flow was measured with a reference flowmeter.

The results of the measurements are summarized below:

- Average inhalation duration: 1.25 sec
- Average exhalation duration: 1.75 sec
- Automatic pause (almost no breathing): 1.5 sec.
- Each breath was measured as containing 550 ml of air, (Tidal Volume VT)

The device provides continuous flow just like the installed mechanical hospital flowmeters. What needs to be confirmed is that there is always enough oxygen flow in relation to the device's breath detection. During inhalation, a condition of under pressure is created in the pneumatic device - oxygen mask. Conversely, an overpressure condition is created during exhalation. The levels of overpressure and under pressure differ in relation to the age, and physical condition of the person. The device monitors the hypo- and over-pressure cycle as described above and this is one of the two patient and breathing pattern detection features. The second feature is the Bluetooth pulse oximeter which is also connected to the SOCS device. By detecting the breathing pattern and the presence of heartbeats (via the Bluetooth pulse oximeter) the programmed oxygen flow is supplied every time. The system can detect breathing patterns with a differential pressure of up to ±10 mbar.

In order to be able to perform oxygen treatments on patients of different age, physical condition and body weight the SOCS can be programmed to 7 different levels of oxygen flow as shown below Table 2. For each setting, flow measurements were performed with a reference flowmeter in series to evaluate the accuracy of the SOCS.

Flow Set of SOCS (lpm)	Corresponding Flow Out *(lpm)*	Reference Flow meter Out *(lpm)*
1	0	0
2	2.5	2.45
3	5	4.9
4	7.5	7.45
5	10	9.9
6	12.5	12.38
7	15	14.9

Table 2: SOCS flow measurements.

In Fig. 12 are summarised the results of table 1. The measurements are within the expected range according to the original design study of the device. Excellent matching with the reference flowmeter is observed.

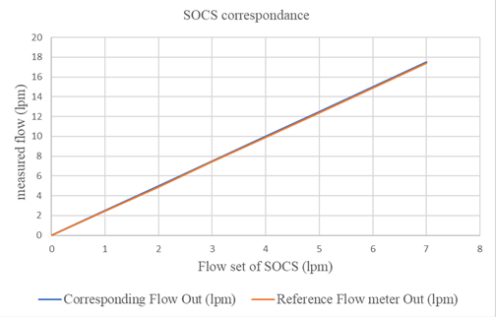

Figure 12: SOCS flow measurement

4. Conclusions

A smart oxygen control system was developed based in mems pressure sensors both absolute and differential. The device is able to detect the existence or not of a patient and its breathing profile. Depending on the treatment prescription for the particular patient the SOCS can supply the required amount of oxygen. SOCS also sends (and receives) information wirelessly to the hospital database. Inline measurements with reference flow meter verify the accuracy of the SOCS's supplied flow. The sensors responsible for the final oxygen supply and the prototype device performance were tested on the main functions. The total error between the measured out flow of the device and the calibrator is below 0.1%. The performance of the differential pressure sensor in terms of resolution and accuracy and its ability to distinguish the weak breathing signal in the worst conditions as reported in the literature for the breathing patterns of adult patients on oxygen therapy, was beyond expectation. The sensor is capable of picking up a 50% weaker breath signal.

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