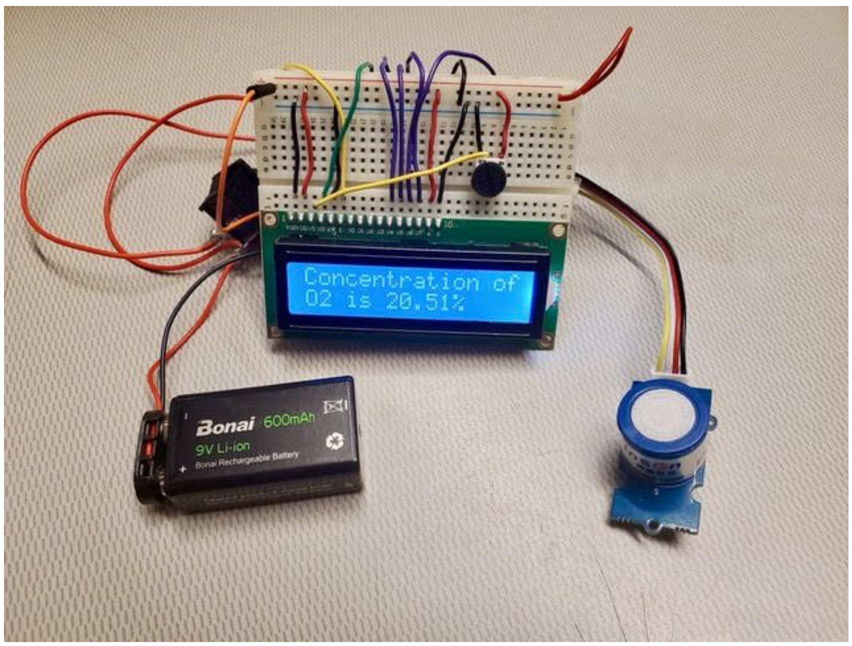
$SENSO_2R$: A Low-Cost Oxygen Analyzer



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Project Definition

Oxygen treatment is used to save the lives of many patients in countless clinical cases. It is an essential tool in the treatment of hypoxia or hypoxaemia, which are side effects of several prevalent diseases in the developing world such as pneumonia, bronchitis, sepsis, and malaria. Traditionally, the gas is administered bedside or during surgery via oxygen cylinders. Unfortunately, oxygen cylinder use and maintenance is associated with a high cost. Due to its transport requirements, infrastructure needs, and cost, cylinder-based oxygen delivery systems are in short supply in the developing world. An alternative to oxygen cylinders is an oxygen concentrator. Oxygen concentrators work by using zeolite to filter oxygen from the air and concentrate it for medical use. While concentrators have lower maintenance needs than cylinders, they are prone to misuse and malfunction. The zeolite filter on a concentrator must be continuously tested to ensure the oxygen concentration being outputted from the machine is above 82%. However, many of the testing methods used in resource-poor settings are only rough estimates. For example, some hospitals use a bottle-match method, where a glass soda bottle is used to capture oxygen from the concentrator and a match is lit inside the bottle to estimate the purity of the gas. The amount of time the match burns is used to estimate the concentration of oxygen.

There are existing technologies for analyzing oxygen concentration; however, they are unrealistically expensive for accessible use in developing countries. Lower-tier analyzers can cost around $200, and higher-quality ones cost upwards of $700. The lack of a proper oxygen analyzer can be devastating for a patient, particularly in cases where the concentrator is producing oxygen with a lower concentration than that of ambient air. Therefore, there exists an urgent need for an economical and low-maintenance method of verifying the concentration output of oxygen concentrators.

We designed an oxygen analyzer that is low-cost, while remaining easy to use and maintain. It is a simply-designed circuit using an Arduino, oxygen sensor, and LCD display, which will allow for fast and straightforward oxygen concentration verification. Our oxygen analyzer is currently a first iteration / proof of concept prototype that can accurately report oxygen concentrations from a range of 0 to 25%. Future iterations of the analyzer will be able to report a concentration range of 0 to 100%, while maintaining its low cost and usability. Our analyzer aims to improve the efficiency of resource-poor hospitals in delivering oxygen therapy and ensure the safety of patients in those hospitals when receiving those therapies.

Impact in the Developing World

There is currently a need for a cheap, efficient, and safe oxygen analyzer in developing countries. Functional and accessible oxygen analyzers are not common in low-resource settings, so doctors in these areas have developed a method using a match and bottle. This protocol involves lighting a match, putting it into a glass soda bottle filled with ambient air, and timing how long it takes for the match to burn out. Then, a soda bottle is filled with oxygen from the oxygen concentrator and the process is repeated. Assuming that the change in burn time and oxygen concentration is correlated, the oxygen levels from the concentrator can be estimated. This method is inconsistent and inexact and thus not reliable for testing the output of the oxygen concentrator.

Medical devices often go unused, either because they break down and cannot be fixed or replaced, or because hospital staff are unsure of how to operate them safely. By enabling health care workers to test their oxygen concentrator, they can use the equipment knowing that it is working properly and therefore reduce risk to their patients. One advantage of our proposed design is that we plan to include easy to understand instructions on use, maintenance, and repair. We also plan to have backup components included with our device. Thus, if our device fails, the design will be modular enough so that broken parts can be easily replaced with new parts. Another advantage of our proposed design is that it will display numerical measurements of oxygen concentrator for the user. This provides greater convenience to the medical staff compared to the soda bottle method, as they can obtain an accurate reading of the oxygen concentration and no longer rely on estimation methods. In critical conditions, this accuracy has the potential to save lives as well as improve the level of treatment for every patient.

The design is a low-cost solution compared to oxygen analyzer products on the market. It can be powered by either non-rechargeable or rechargeable AA or AAA batteries, instead of power outlets which may be more unreliable in the developing world. Users can choose to use rechargeable batteries that are provided to them along with the device, or choose to use non-rechargeable batteries that might already be available in the hospital.

Our project aims to overcome the hurdles associated with oxygen delivery in low-resource healthcare settings. The foundational pillar of Engineering World Health is to lessen the healthcare disparity, and our project aims to do so by offering an efficient, accurate, and accessible oxygen analyzer.

Required Performance Specifications

Our design works as a proof of concept for a medical-grade oxygen analyzer. The device must be capable of detecting oxygen concentrations of at least 20%, which will be assessed by testing the concentration of oxygen in the air (typically around 20-21%) [1]. The device also must be capable of accurately testing oxygen concentrations below atmospheric levels (less than 20-21%). This is necessary because the concentration of oxygen being delivered to a patient cannot fall below the atmospheric content without risking asphyxiation. Our design requires that the analyzer have a total working life of at least 2 years to enhance the usability of the device and to ensure replacements parts for the device are needed less frequently. This minimizes the risk of the device wearing out and becoming inaccurate while within the recommended usage period.

To maximize the reusability and minimize the cost of the device, the device should be powered using a rechargeable source, such as 9V lithium ion batteries. One fully charged battery should allow for at least 3 hours of use, and the battery should be able to be recharged numerous times. Most oxygen concentrators need to have cleaning and maintenance performed on them weekly [2]. Thus, we envision the device being used weekly to periodically check the concentration of oxygen being produced by medical oxygen concentrations, and thus over 2 years, we would need the battery-powered device to be operable over a period of 104 days (324 hours). Additionally, oxygen readings should not significantly change when the voltage supplied by the battery is above or below the threshold needed for the device to work. This would ensure that even when the battery is not fully charged, the oxygen readings will still be accurate. Finally, the device must not still operate and give oxygen readings when the voltage supplied to the device is less than the threshold voltage value needed for the device to operate. This prevents inaccurate readings and allows users to easily recognize when the battery needs to be replaced.

Implementation of Prototype

Our prototype of the oxygen analyzer consists of a handful of components. One of the components used is an oxygen sensor that can be integrated with a circuit. We chose the Grove oxygen sensor due to its functionality and its compact size. It is shaped like a cylinder and measures 20 mm in diameter, and can be seen in Figure 1 below.

Figure 1: Grove Oxygen Sensor

The oxygen sensor is connected to a microcontroller module (Elegoo Uno R3), which controls the operation of the oxygen sensor. When connected properly, the oxygen sensor will produce a voltage that is proportional to the amount of oxygen in the air the sensor is in. We connect the sensor to our arduino, and to provide the user with a convenient way to read oxygen concentration, an easy-to-read liquid crystal display (Elegoo Uno R3 LCD1602) is connected as well. The oxygen sensor, microcontroller, and LCD display are powered by a 9V rechargeable lithium-based battery. The lithium-based battery (BONAI 600mAh 9V Lithium-ion battery) was chosen because it has a longer life cycle than an alkaline-based battery. An on-off switch was also integrated into the circuit so that the user can power on the oxygen sensor as desired. To help with organization, these components are also assembled on a solderless, half-sized plug-in breadboard with 30 rows and 8 columns.

Our prototype is first constructed by appropriately connecting the oxygen sensor to the microcontroller. For the Grove oxygen sensor, there are three protruding wires. The wires collecting data from the sensor are connected to the analog A1 and A3 pins in the microcontroller. The other two wires are connected to the corresponding 5V and ground terminals on the breadboard, to power the sensor. The liquid crystal display is connected to the breadboard and then to the digital input and output pins. In addition, a potentiometer is included in the LCD display to help adjust the LCD screen brightness to the preferred level by the user. The lithium-based battery is placed into a battery housing, and the wires from the battery housing are plugged into their respective V-in and ground terminals on the breadboard. Between the V-in terminal and the battery, an on-off switch is also connected. A picture of the full layout is shown below in Figure 2.

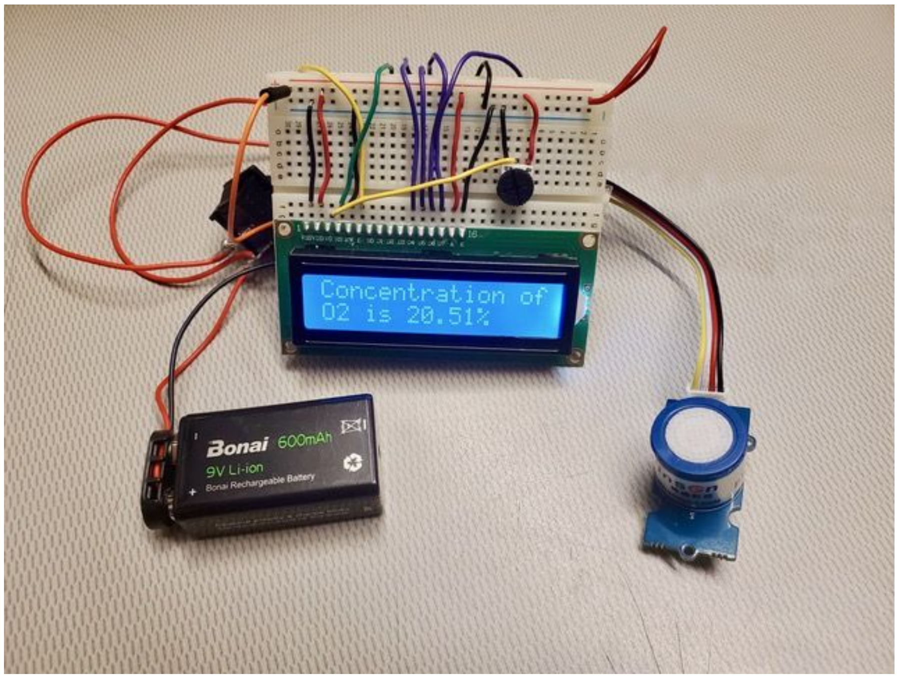

Figure 2: Prototype 1 of Oxygen Analyzer

To operate our prototype, the sensor should be powered up and preheated beforehand for 20 minutes by flipping the switch to the on-position 20 minutes before use [3]. The user would then adjust the potentiometer knob until the LCD is of an appropriate brightness. The oxygen sensor component is directed towards the source of oxygen. The source of oxygen should be placed sufficiently close to the oxygen sensor component to ensure that the surrounding air of the sensor should be almost saturated with the air to be measured. The distance between the oxygen source and the sensor should be as close as possible without touching the surface of the sensor.

Proof of Performance

Our oxygen analyzer must be capable of accurately testing the concentration of oxygen in the air, which is approximately between 20-21%. The Grove oxygen sensor we utilized in our device needed to be initially calibrated. Thus, the oxygen sensor was allowed to equilibrate with atmospheric oxygen in the air, and the Arduino code (see Appendix A) used by the device to sense oxygen was modified so that the LCD readout was 20.5% oxygen concentration. To ensure that this reading was reliable, we tested the oxygen concentration of expired air of 2 different subjects. The oxygen concentration of expired air is known to be around 15-16% [4]. Two subjects flattened a balloon to remove all atmospheric air and breathed into it. The balloon was attached to the oxygen sensor, and the expired air and the sensor were allowed to equilibrate. The oxygen concentration reading before and after exposure to the expired air was recorded. This data for 2 subjects is seen below in Table 1.

Table 1: Oxygen concentration data for two subjects breathing expired air

Subject	**Trial**	**Atmospheric O_2 (%)**	**Expired Air O_2 (%)**
Subject 1	Trial 1	20.45	15.22
	Trial 2	20.45	15.07
	Trial 3	20.43	15.32
Subject 2	Trial 1	20.45	17.60
	Trial 2	20.50	17.50
	Trial 3	20.50	17.42

For both subjects, the average atmospheric oxygen concentration detected before exposing the device to expired air was 20.45%, proving that the analyzer could consistently and accurately detect atmospheric oxygen even after several perturbations such as analyzing the oxygen content of expired air. Looking at the expired air trials, Subject 1 had an average expired air oxygen concentration of 15.21% and standard deviation of 0.13%, while Subject 2 had an average of 17.51% and a standard deviation of 0.07%. The differences in these two average values can likely be attributed to differing respiratory quotients for each subject, which depend on factors such as time spent awake and type of food eaten / metabolized. The more revealing data is the similarity of expired air oxygen concentrations over multiple trials detected by the analyzer, as both subjects had very small standard deviation values (0.13% and 0.07%, respectively). Additionally, both average expired air oxygen concentrations values are in or close to the range of 15-16%, which is the expected value for expired air. Thus, we can conclude that our sensor calibration was performed correctly and we can thus accurately detect atmospheric oxygen levels and oxygen levels that are less than 20%.

Oxygen readings from the analyzer should not significantly change even when the battery is not at full charge. A voltage divider was built to decrease the amount of voltage supplied from the battery that reached the analyzer, and atmospheric oxygen readings were recorded at different voltage values, seen in Table 2.

Table 2: Atmospheric oxygen concentration output at different battery voltages

Voltage Received by Arduino (V)	Atmospheric O_2 (%)
9	20.45
7	20.41
5	20.32
4	No readout

As seen by the atmospheric O2 readings at decreasing voltage values, the oxygen readout does not significantly change as long as the voltage supplied is above the minimum voltage needed by the Ardunio to turn on the LCD (5V). As seen by the 4V data point, the LCD display has no readout when the input voltage is less than 5V, which is desirable as this indicates the battery needs recharging without producing an erroneous oxygen concentration value.

Given the desire to use the analyzer weekly for 2 years and for a maximum of 3 hours at a time, the components of the device that are subject to failure over time (the Grove oxygen sensor and the 9V lithium ion batteries) must be able to operate over 2 years and a total of 324 hours. The Grove oxygen sensor has a lifetime of at least 2 years, and thus is capable of accurately detecting oxygen over this time frame. Additionally, a fully-charged 9V battery was able to power our analyzer for around 3 hours, thus meeting the requirement of operating the device for a maximum of 3 hours at a time. Additionally, the BONAI 9V lithium-ion batteries utilized in our device are capable of being recharged 1200 times before losing charging capability [5]. Thus, 1200 uses at 3 hours maximum per use yields 3600 hours of oxygen sensing capability, well exceeding the 324 hours we plan for the analyzer to be implemented.

Business Plan

Often the most challenging aspect of developing a medical device for a low-resource setting is not the development of the technology itself, but implementing a business plan that allows the device to enter the market successfully. From choosing suppliers and a method of distribution to who will be the target customer, there are unique considerations that must be made when creating a business model for the developing world. It is important to note both the similarities and differences, and also common misconceptions when organizing the business plan. First, we chose our customer base and deduced which organizations we would want to potentially partner with. Our target market would be clinics and hospitals that perform surgeries or any procedure in which patients have to undergo anesthesia. Although surgical wards would be a primary focus, this design could be implemented with any oxygen treatment to ensure quality oxygen is being delivered.

We had to get a better understanding of what our limitations are as far as skill sets and knowledge of our market goes, and we determined that the best way to gain this knowledge would be through partnerships with NGOs, businesses, and universities. Since our project was initially scoped in Tanzania, we will focus our business plan in Tanzania. We would initially partner with Tanzania Health Promotion Support (THPS), an indigenous NGO that works in conjunction with the Ministries of Health, Community Development, Gender, Elderly and Children (MoHCDGEC). They also work with local governments across the country, and their goal is to ensure all Tanzanians have access to high quality health care. THPS works with over 600 healthcare facilities across Tanzania. Their main focus is HIV treatment and prevention, however with their roots in the country and their broad network we believe we could find a mutually beneficial partnership with them. By partnering with THPS, we are able to gain access to their network for fundraising to help cover the costs involved in implementing our oxygen sensor as well as more intuition on how best to distribute this device. As an NGO with experience in philanthropic efforts , THPS has the ability to reach a widespread network of people invested in improving the Tanzanian community and the healthcare provided there. With these connections, we could minimize costs for clinics and hospitals with limited resources. Additionally, their first-hand experience working in the field offers knowledge of the communities that we aim to improve. Thus, their staff will be instrumental to planning and executing the best methods for us to distribute devices, train healthcare providers, and manage repairs and replacements.

The development of the technology used in the device is fairly simple. It is comprised of four simple parts: the LCD, Arduino, sensor, and circuit components. The arduino code would be stored, and, in large scale production could be readily downloaded onto, the microcontrollers in production. Since the code is already developed, the technology itself does not require much funding. The only costs involved in producing the product are associated with the raw materials and the manufacturing of the device itself. As mentioned previously, our partnership with THPS opens the door to having the cost of the product being mostly covered through donations from individuals and companies. Initially, however, this project will require a startup investment. However, this could be crowdsourced through a fundraising network. In order to make the costs of this technology more sustainable, the assembly of the product will be in Tanzanian communities, assuring that the job market within Tanzanian communities benefits alongside healthcare. There will, however, be costs involved with the distribution and building of our network, just as with any company. Most often small companies have to go through angel investors and venture capitalists to get the funds to jump start the business [6]. Additionally, as detailed by Malkin et al, the best method of distribution is by finding a contract manufacturer and going through the traditional channel of distribution - selling. Trying to get a new medical device into low-resource settings is often seen as not profitable because it is a challenging market, but simply donating devices and subsidizing actually hinders the prospects of dispersing a novel medical device.

Since this is the first generation of our device, part of what we would like to do differently in the next iteration is to make it more easily manufacturable. Currently, we are using a half sized breadboard and wires to connect our LCD screen and oxygen sensor to our arduino. What would be better to use in the future, since our circuit is rather simple, is a printed circuit board (PCB). In order to keep the manufacture of the PCB local to East Africa, we would like to establish a partnership with Sahasra Electronics. Sahasra is an India-based company, but has a location in Kigali, Rwanda. We would have Sahasra Electronics make the PCBs we would need, which would be shipped to an original equipment manufacturer (OEM) in Tanzania to build our final product. We hope to find business opportunities that will allow us to integrate our device into the local economies we are designing it for, rather than just sell it to these communities. We will follow the ISO 13485, which lays out the standard for medical device manufacturing. We will take this into consideration because, since this is not a life-saving medical device, it does not need approval by a review board in Tanzania. However, in order to promote the quality of our product we will follow the guidelines laid out here.

Works Cited

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Appendix A: Arduino Code

```
#include <math.h>
#include <LiquidCrystal.h>

const int buzzerPin=3;//Connect the Buzzer Grove module to Pin3,
Digital 3
float WarningValue=19.5;//The minimum state concentration of O2 in
air

LiquidCrystal lcd(7, 8, 9, 10, 11, 12);

void setup() {
  // put your setup code here, to run once:
    Serial.begin(9600);
    Serial.println("Grove - Gas Sensor Test Code...");
    lcd.begin(16,2);
}

//Yellow wire is A3, white wire is A1
void loop() {
  //long unsigned a;
  float sensorValue;
  float sensorVoltage;
  float Value_O2;
  sensorValue = analogRead(A3);
  sensorVoltage = (sensorValue/1024)*5.0;
  sensorVoltage = sensorVoltage/201*10000*2.07;
  Value_O2 = sensorVoltage/7.43;

  lcd.setCursor(0, 0);
  lcd.print("Concentration of");
  lcd.setCursor(0, 1);
  lcd.print("O2 is ");
  lcd.setCursor(6, 1);
  lcd.print(Value_O2);
  lcd.setCursor(11, 1);
  lcd.print("%");

  //Serial.print("concentration of O2 is ");
  //Serial.print(Value_O2,1);
  //Serial.println("%");
```

```
/*
if(Value_O2<=WarningValue)
{
  digitalWrite(3,HIGH);
}
else digitalWrite(3,LOW);
delay(1000);
*/
}
```