Design of low-flow oxygen monitor and control system for respiration and SpO₂ rates optimization

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Abstract. The importance of respiration rates and oxygen saturation (SpO₂) monitoring and the high need for oxygen therapy opens the opportunity for the development of non-invasive respiration rate and oxygen saturation monitoring and controlling system. There are two modes of controlling in this system, automatic and manual mode. In automatic mode, the oxygen flow rate is based on the measurement of the respiration rate using the MLX90614 temperature sensor and tidal volume determination based on the patient's body weight. Oxygen flow control uses a DC motor to open and close the oxygen regulator valve. Oxygen flow will stop when the respiration rate and oxygen saturation level are normal. Oxygen saturation is measured using the MAX30100 sensor. The fabricated regulator control system is capable of flowing oxygen by 5-8 liters per minute using an oxygen mask. The respiration rate measurement was compared with the palpation test, and the deviation was 0.99%. Oxygen saturation reading that used MAX30100 as an oximeter sensor was compared with pulse oximeter fingertip reading, and the deviation was 1.62%. The average flow deviation between the fabricated regulator control system and the calibrated regulator is 2.93%. The result of measuring the response time of the motor for an increase of one liter per minute (LPM) is 1.54 seconds.

1. Introduction
Oxygen is an important element for life and without oxygen humans can survive for a few minutes only. There should be a balance between oxygen demand and supply to defend homeostasis within the body. The two main organ systems responsible for oxygen supply in the body and maintaining homeostasis are respiratory and cardiovascular [1]. Respiration is the process of inhalation of oxygen and exhalation of carbon dioxide [2].

Table 1. Respiration rate based on age group [3]

| Age group       | Respiration rate (per minute) |
|-----------------|------------------------------|
| New-born and infants | 30 – 60                      |
| Infants         | 24 - 30                      |
| Toddlers        | 20 – 30                      |
| Children        | 12 – 30                      |
| Adults          | 8 – 20                       |
Abnormal function of any of these two would lead to the development of hypoxemia and its detrimental consequences [1].

Hypoxemia is a condition of decreased oxygen concentration in arterial blood (PaO$_2$) or arterial oxygen saturation (SaO$_2$) below normal (normal PaO$_2$ 85-100 mmHg, SaO$_2$ 95%). In neonates, PaO$_2$ <50 mmHg or SaO$_2$ <88%. In adults, children and infants, PaO$_2$ <60 mmHg or SaO$_2$ <90% [4]. It can be due to either defective delivery or defective utilization of oxygen by the tissues [1].

Oxygen saturation is the percentage of oxygen that can be carried by hemoglobin. SaO$_2$ is the oxygen saturation of the arteries measured by blood analysis, while SpO$_2$ is oxygen saturation detected by the pulse oximeter. Pulse oximetry is used as a standard for monitoring hypoxemia and administering oxygen therapy to patients [5]. The higher the RR value, the lower the SpO$_2$. This shows that the increase in RR is an indication of the body's compensation mechanism to maintain tissue perfusion [6].

The amount of air that enters and exits the lung each time breathing is called tidal volume (TV). In oxygen administration, tidal volume is delivered oxygen, which depends on the patient's body weight of 4-6 ml/kg to protect the lungs. The oxygen demand flowed through the airways per minute can use equation (1).

\[
MV (L / minute) = \frac{TV(ml) \times RR(\text{per minute})}{1000ml / L}
\]

MV (Minute Ventilation) is the amount of air that enters the respiratory tract every minute. RR (Respiratory Rate) is the number of breathing cycles (inspiration and expiration) [7].

O. therapy is one of the respiratory therapies in maintaining adequate tissue oxygenation. The method of giving O. can be divided into two techniques, these are low-flow system and high-flow system. The main purpose of giving O. is to overcome the state of hypoxemia following the results of blood gas analysis, to reduce the work of breathing, and reduce myocardial work. The detrimental effect of administering oxygen if it is not monitored is that it can suppress ventilation and oxygen poisoning if given for a long time with high concentrations [8]. So, a monitoring and control system is needed to administer oxygen to the patient. In this study, the used technique is a low-flow system using an oxygen mask with flow 5-8 liter/minute.

The oxygen regulator monitoring and control system helps medical staff monitor respiratory rates and SpO$_2$, and control oxygen regulators. The fabricated system is a monitoring and controlling system of an oxygen regulator automatically and manually. Automatic oxygen regulator control based on respiration rate (RR) and the bodyweight of the patient. While the manual oxygen regulator control regulates the motor rotation to open or close the oxygen regulator valve, based on the keypad input.

The fabricated system used two sensors. The sensor used to measure RR is the MLX90614 temperature sensor. The MLX90614 sensor can calibrate infrared radiation energy to a temperature scale [9]. The sensor used to measure SpO$_2$ is MAX30100. The MAX30100 sensor can be used to measure oxygen saturation levels in % SpO$_2$ and heart rate in beats per minute (bpm). MAX30100 sensor is a pulse oximeter reflectance type sensor [10]. Both of these sensors will be input for monitoring mode.

To change the oxygen regulator control mode, this system uses a slide switch. Switches are the basic components in the electrical circuit and the system control circuit. Its main function is connecting, disconnecting and changing the direction of the electrical connection. Switches consist of various types including this slide switch. Most slider switches (also known as slide switches) have two positions and function as SPDT or DPDT switches [11].

The output of this system is the flow of oxygen which is controlled by a DC motor equipped with a gearbox. DC motors need to be equipped with gearboxes for most applications, due to their high free
speed and low torque. The speed of this DC motor is controlled by the Pulse Width Modulation value [12].

2. Methods

2.1 Hardware Design
MLX90614 sensor, MAX30100 sensor, potentiometer, keypad, push-button, and 12 Volt adaptor are inputs for the microcontroller. The system output is a 20x4 LCD, LED indicator, and DC motor rotation. The microcontroller used is Arduino Mega. The hardware design of the monitoring and controlling system is shown in Figure 1. The diagram block of the oxygen regulator in automatic mode is shown in Figure 2.

![Hardware design of monitoring and controlling system](image1)

![Diagram block of oxygen regulator control system in automatic mode](image2)

2.2 Software Design
In this fabricated system, monitoring mode is the first mode to be active when the device is turned on. The function of this mode is to monitor the patient's initial condition. The measurement results in this mode determine whether the patient needs oxygen or not, based on normal and abnormal respiratory conditions. Abnormal conditions, i.e. if the number of breaths >20 breaths per minute and/or if the oxygen saturation value is <90%. If one or both of these abnormal conditions occur, the buzzer will turn on.

There are two control modes on this system, automatic and manual. A slide switch is used to change control mode. The program design for monitoring and control systems is presented in Figure 3.
3. Result and Discussion

3.1 Prototype Fabrication
This monitoring and control system uses an AVICO oxygen regulator with an additional acrylic box and a DC gearbox motor. This DC motor to activate the oxygen regulator valve. The physical form of the oxygen regulating system and the placement of sensors is shown in Figures 4, 5, and 6.
3.2 Prototype Testing

The process of breathing (respiration) is divided into two distinct phases, inspiration (inhalation) and expiration (exhalation). Measurement of inspiration and expiration can be done based on measurements of the temperature when inspiration and expiration. The expiration temperature is higher than the inspiration temperature. Temperature change is detected by the MLX90614 sensor. RR measurement results using this sensor are compared with the results of the palpation test (observing the motion of the patient's chest cavity). This test was conducted on 10 different healthy volunteers (mean age 22, range 21-23 years).
Table 2. RR measurement results using the MLX90614 sensor

| Subjects | Temperature (°C) | RR (per minute) | Deviation (%) |
|----------|------------------|-----------------|---------------|
|          | min   | max   | MLX90614 sensor | Palpation |
| 1        | 25.4  | 40.6  | 14             | 14        | 0   |
| 2        | 27.7  | 32.3  | 23             | 23        | 0   |
| 3        | 24.8  | 35.7  | 16             | 16        | 0   |
| 4        | 27.7  | 32.3  | 13             | 13        | 0   |
| 5        | 27.8  | 32.7  | 15             | 15        | 0   |
| 6        | 29.2  | 35.3  | 20             | 20        | 0   |
| 7        | 27.2  | 33.2  | 12             | 12        | 0   |
| 8        | 29.1  | 33.0  | 12             | 12        | 0   |
| 9        | 28.8  | 31.9  | 19             | 18        | 5.56 |
| 10       | 29.0  | 34.1  | 22             | 23        | 4.35 |
|          |       |       | Average Deviation | 0.99   |

From RR measurement, the lowest temperature was 25°C and the highest temperature was 40.6°C. The results showed that there was almost no difference in the number of breaths from the results of the palpation test with the results of calculations based on, with the average sensor reading deviation is 0.99%.

Measurement of oxygen saturation by the MAX30100 sensor was compared with the reading of the Fingertip Pulse Oximeter. This test was conducted on 10 different healthy volunteers (mean age 22, range 21-23 years).

Table 3. Oxygen saturation measurement results using the MAX30100 sensor

| Subject | Oxygen Saturation (%) | Deviation (%) |
|---------|-----------------------|---------------|
|         | MAX30100 Sensor       | Fingertip Pulse Oximeter |               |
| 1       | 97                    | 99             | 2.02          |
| 2       | 97                    | 99             | 2.02          |
| 3       | 98                    | 99             | 1.01          |
| 4       | 97                    | 98             | 1.02          |
| 5       | 96                    | 99             | 3.03          |
| 6       | 95                    | 96             | 1.04          |
| 7       | 96                    | 98             | 2.04          |
| 8       | 97                    | 98             | 1.02          |
| 9       | 97                    | 96             | 1.02          |
| 10      | 97                    | 99             | 2.02          |
|         | Average Deviation     | 1.62          |

From the MAX30100 sensor test results obtained the greatest deviation of 2.04%, the smallest deviation of 1.01%, and the average sensor deviation of 1.62%. Thus, the MAX300100 sensor can be used to measure oxygen saturation in a monitoring system for regulating oxygen flow output.

The next test is to determine the performance of the prototype in automatic mode. In this automatic mode, there is a monitoring system (RR measurement by MLX906114 and oxygen saturation measurement by MAX30100) and an oxygen regulator rotation control system by DC gearbox motor.
The oxygen flow rate from the prototype is compared with the calibrated flow rate on the AVICO oxygen regulator. This test was carried out on 5 healthy volunteers with different body weights. This test result is shown in Table 4.

**Table 4. The test result of automatic mode oxygen regulator control system**

| Body Weight (Kg) | RR (per minute) | Measurement and response | Motor Response | Motor time response (second) |
|------------------|-----------------|--------------------------|----------------|----------------------------|
|                  | Manual calculation | Prototype | AVICO | Prototype |                      |                      |
| 45               | 25               | 6.75        | 6.70  | 6.5       | 6.3       | rotates left          | 11.33                |
|                  | 28               | 7.56        | 7.50  | 7.5       | 7.6       | rotates left          | 2.27                 |
|                  | 30               | 8.10        | 8.00  | 8.0       | 7.8       | rotates left          | 0.30                 |
| 49               | 30               | 8.82        | 8.00  | 8.0       | 7.8       | rotates left          | 13.83                |
|                  | 32               | 9.41        | 8.00  | 8.0       | 7.8       | not rotate            | 0.00                 |
|                  | 24               | 7.06        | 7.00  | 7.0       | 6.8       | rotates right         | 2.56                 |
| 50               | 26               | 7.80        | 7.80  | 7.5       | 7.6       | rotates left          | 13.38                |
|                  | 24               | 7.20        | 7.20  | 7.0       | 6.8       | rotates right         | 1.88                 |
|                  | 21               | 6.30        | 6.30  | 6.0       | 5.9       | rotates right         | 1.85                 |
| 54               | 28               | 9.07        | 8.00  | 8.0       | 7.7       | rotates left          | 13.44                |
|                  | 25               | 8.10        | 8.00  | 8.0       | 7.7       | not rotate            | 0.00                 |
|                  | 20               | 6.48        | 0.00  | 0.0       | 0.0       | rotates right         | 13.44                |
| 60               | 28               | 10.08       | 8.00  | 8.0       | 7.7       | rotates left          | 13.61                |
|                  | 25               | 9.00        | 8.00  | 8.0       | 7.7       | not rotate            | 0.00                 |
|                  | 21               | 7.56        | 7.50  | 7.5       | 7.1       | rotates right         | 0.57                 |

The average deviation of oxygen flow (%) 2.94

The response of the motor motion rotating left and right is opening and closing the oxygen flow valve. The average deviation of the oxygen flow measurement by 2.94%.

This prototype applies the monitoring and flow-control system to the oxygen regulator. The monitoring system is based on measurements of respiration rate and oxygen saturation (SpO₂). The fabricated regulator control system is capable of flowing oxygen by 5-8 liters per minute using an oxygen mask. The result of measuring the response time of the motor for an increase of one liter per minute (LPM) is 1.54 seconds.

In the control system, there are manual and automatic modes. Manual mode can be used by trained users (such as doctors or nurses), who already have knowledge of the patient's oxygen needs. Automatic mode can be used by trained users and laypeople. The provision of oxygen flow will be based on a prototype monitoring system that is based on RR, body weight, and oxygen saturation. Oxygen flow stops when the RR and oxygen saturation is normal. So the patient will not get excess oxygen. In addition, this system can save the use of oxygen because it can be adjusted to the needs of patients.

This prototype monitoring and control system produces a small average deviation, under 3%. This prototype can be used by outpatients and also patients who need a continuous respiration rate and oxygen saturation monitoring system. In the future, this prototype can be integrated with internet communication so that measurement results can be monitored directly by medical personnel.

4 Conclusion
The monitoring system is based on RR measurement using the MLX90614 temperature sensor. Based on this RR measurement and body weight, minute ventilation or oxygen flow rate can be determined. Oxygen flow is regulated by a DC motor that can rotate the oxygen regulator valve. The fabricated regulator control system is capable of flowing oxygen by 5-8 liters per minute using an oxygen mask. Oxygen flow stops when the RR and SpO2 values are normal. The SpO2 measurement uses the MAX30100 oximeter sensor. The RR measurement results using a prototype compared to the palpation test, and the deviation was 0.99%. Oxygen saturation reading that used MAX30100 as an oximeter sensor was compared with pulse oximeter fingertip reading, and the deviation was 1.62%. The oxygen flow rate from the prototype is compared with the calibrated flow rate on the AVICO oxygen regulator. The average deviation of the oxygen flow measurement by 2.94%.

Acknowledgments
Authors wishing to acknowledge assistance or encouragement from Electronics Instrumentation, Polytechnic Institute of Nuclear Technology and financial support from Unit of Research and Community Service of Polytechnic Institute of Nuclear Technology, also National Nuclear Energy Agency of Indonesia.

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