METHODS OF MEASURING FUNCTIONALITY PARAMETERS AND EFFICIENCY FOR LOW CURRENT SOLAR MODULES

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ABSTRACT: This paper proposes cost effective methods of measuring the efficiency and parameters of solar modules that present low currents. The measurements can be conducted with a set of sensors connected to a hardware/software platform named Arduino that is based on a microcontroller which can transform the input received from the sensors into information that can be interpreted by the user. The goal of this measurement system is not only to record the output parameters of the module, but also to record the environmental conditions such as the incident solar radiation, the environmental and module temperature and also the illumination level.

KEY WORDS: Photovoltaics; Arduino; Data acquisition

1. INTRODUCTION

The study of solar modules behavior in different environmental conditions can provide a valuable insight regarding their efficiency. The most important parameters that must be measured consist of the electrical output parameters of the module (open circuit voltage, short circuit current, maximum power point, voltage and current at the maximum power point). One major concern regarding low current solar modules is the difficulty of finding a right load resistor in order to obtain the maximum power output under illumination conditions that are not ideal, this issue occurs due to the fact that the characteristic resistance of the module varies with the irradiance level, and in order to transfer the maximum power point from the module to the load, the two resistances must match. The maximum power stated in the technical specifications of the module is obtained at Standard Test Conditions which involve an incident radiation of 1000 W/m^2 and a temperature of 25 ºC, but in real measurements that level of radiation hard to obtain, especially at high latitudes, so in order to find a right load for the module the user must know the characteristic resistance of the solar module at the irradiation level under which the measurement is conducted. The characteristic resistance can be estimated as a ratio between the open circuit voltage and the short circuit current so knowing these two parameters can lead to an easy way of reaching the peak power. [1]

Measuring the evolution of the voltage and current while varying the load resistance from a very low value to a very high one can also provide the I-V characteristic of the solar module. This characteristic is a valuable way to determine the efficiency of the module and also to identify the parameters that can reveal a faulty module such as parasitic resistances.

These parameters can be recorded with a hardware/software platform called Arduino. This platform is based on a microcontroller that can receive, process and send information towards other devices connected to it. If this platform is used to receive data from sensors the input part of the microcontroller is of interest. Depending on the type of sensor connected Arduino can either receive analog signals on a range between 0 and 5V with a resolution of 4.9 mV per unit through its six analog pins or it can receive signals from digital sensors on its digital pins. [2] The software part of Arduino can provide a convenient way of performing calculations and estimations based on the input received from the sensors so in the case of this study, the value of the incident irradiance can be estimated with a formula that involves the measured value of the short circuit current. Also, other parameters such as the temperature and illumination can be recorded simultaneously and are used to evaluate the behavior and efficiency of the module.

2. MATERIALS AND METHODS

Measuring the numerous parameters of a solar module simultaneously can be a difficult challenge but by choosing the right set of sensors this goal can be achieved. In this study the parameters that are to be measured consist of currents, voltages, temperatures and illumination levels.

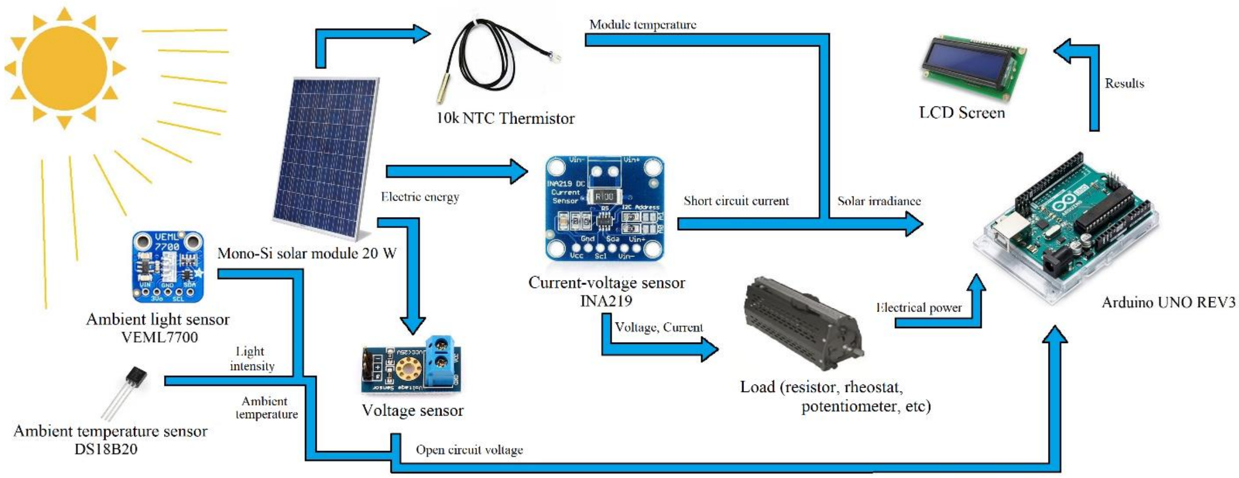

Figure 1. Sensors used for measurements conducted on the solar module [3]

The current can either be the one obtained at short circuit conditions or the one obtained with a load in the circuit. Measuring the current of a solar module without a multimeter can prove to be a difficult task, especially if the module has a low current. The solar module used in this study has a short circuit current that can reach 1.18 A at STC conditions, so in real conditions the current is expected to have a value below 1 ampere. Measuring such low currents with a microcontroller is difficult because most sensors are made to measure currents above 1 A with a very low precision on currents that are below 0.5 A. The solution to this problem is the use of the bidirectional current/voltage sensor called INA219, this sensor has an in-built shunt resistor of 0.1 ohms and can measure small currents starting with 1 mA up to 3.2 A with a precision of 0.8 mA. [4] As the name states, the sensor can also measure voltages, so it can either measure the short circuit current or it can measure the current and voltage that go through a load at the same time without the need of a voltage sensor.

However, a voltage sensor is needed in order to measure the open circuit voltage. Because the open circuit voltage involves the presence of an infinite resistance, the current/voltage sensor would need to have a load resistor with a very high resistance value in order to drain all current out of the circuit, but in low light conditions when the characteristic resistance of the module is high, that resistor might not drain all current and the open circuit voltage readings might be faulty, so the use of another voltage sensor can solve this problem. One important aspect involves the fact that the short circuit current, the open circuit voltage and the power obtained through a load cannot be measured at the same time. Each of these three parameters must be measured separately because if they are measured together, the short circuit current will become the only readable parameter. The solution to this problem is to divide the circuit into three branches by inserting three switches that can allow the user to choose which parameter to measure at a certain time by closing only the circuit whose parameters are of interest.

Measurements of temperature can provide a valuable information about its impact on the module's performance. The temperature of the module is measured through a thermistor which is basically a heat sensitive resistor that is attached to the back of the module. The resistance of the thermistor will decrease once its temperature increases so measuring its resistance is an effective way of recording the module's temperature. Measuring the resistance of the thermistor can be done by establishing a voltage divider consisting of the thermistor and a 10 kiloohm resistor that is inserted in the circuit. When feeding that voltage divider with 5V from the Arduino chip, the variations on the output voltage will point out the resistance of the thermistor R_2 and by using the Steinhart-Hart formula the temperature T can be easily extracted. [5]

$$\frac{1}{T} = A + B \cdot lnR_2 + C \cdot ln(lnR_2)^3 \qquad (1)$$

The terms A, B and C are called Steinhart-Hart coefficients and they vary with the type of thermistor used but they are usually mentioned in the thermistor's datasheet. On the other hand, the ambient temperature can be more easily recorded through a digital sensor called DS18B20.

The ambient illumination level is measured through a sensor called VEML7700, this sensor can measure light intensities between 0 lux and 120 kilolux with a resolution of 0.0036 lux per unit. [6] The main advantage of this sensor is that it can measure very high irradiance levels so it can even measure the light coming directly from the Sun without requirements of using a protective mesh. This sensor communicates on the I2C protocol, functionality that is shared with the current sensor INA219 but this does not pose a problem because each sensor has its own address and the microcontroller can read data from them independently.

The information received from the sensors can be either displayed on a computer or laptop but if the tests are conducted on a remote location for a long time and a desktop device cannot be used, a LCD display and a datalogger can be a convenient solution.

The short circuit current and the module temperature can be used to approximate the incident solar irradiance on the module through the following formula [7]:

$$G = \frac{1000}{I_{SC\_STC}} \cdot [I_{SC} - \mu_{Isc} \cdot (T - 25)] \quad (2)$$

The effect of temperature will have an impact on the readings of the solar irradiance once the temperature exceeds 25 ºC as the value of the short circuit current will slowly increase. So, the short circuit temperature coefficient of the module μ_{Isc} is needed to compensate for this increase in the current. This temperature coefficient is sometimes specified by the manufacturer buy if it is not, a coefficient that corresponds to the type of the module can be used. In this study the coefficient was not mentioned but as the module was a monocrystalline one the short circuit temperature coefficient was assumed to have the value of 0.401 mA/ºC. [8]

The estimation of the incident irradiance through the microcontroller can become very helpful in calculating the efficiency of the module, because the use of a very expensive device for measuring the irradiance called pyranometer is no longer needed. The efficiency can be calculated after plotting the I-V curve of the module taking in account the irradiance level E that was recorded when the measurements were conducted. Once the maximum power point has been identified and the surface of the module "A" has been measured the efficiency can be calculated with the following formula [9]:

$$\eta = \frac{Pmax}{E \cdot A} \cdot 100 \quad (3)$$

Another important efficiency related parameter is represented by the fill factor. This parameter can indicate how much the voltage and the current at the maximum power point have decreased from the values obtained at the open voltage point and short circuit point respectively. The fill factor will always have a value below 1 and can also be expressed as a percentage. An ideal solar module will have a fill factor equal to 1, meaning that the voltage and current of the module do not vary with the load, but real solar modules have fill factor values between 70% and 85%. [10]

$$F = \frac{Pmax}{V_{oc} \cdot I_{sc}} \cdot 100 \quad (4)$$

Once the IV curve of the module has been obtained the values of the parasitic resistances can also be calculated as they have an impact on the fill factor and also on the efficiency. The parasitic resistances consist of the series and shunt resistance.

Series resistance R_S has a great impact on the voltage, especially on the open circuit one and can be obtained by calculating the slope of the I-V curve near the open circuit voltage. [11] This can be done by selecting a few recorded points and calculating the slope in a program that has statistical functions such as Microsoft Excel. Once the value of the slope has been obtained, it's inverse will give the value of the series resistance. The only problem in measuring the series resistance in low current solar modules, especially in low light conditions is the need of high load resistances in order to obtain a very large value of the voltage. The replacement of the resistor can be time consuming and must be done fast as the variations of the irradiance can alter the results. In very low light conditions when the characteristic resistance of the module is really high a potentiometer can be an easy solution for this problem.

The shunt resistance R_{SH} on the other hand is easier to measure. It impacts the current especially the one near the short circuit point. It can be calculated as the slope of the I-V curve near the short circuit current point. [12] Just as in the case of the series resistance, a few points measured with a low resistance load can give the slope and its inverse is the value of the resistance.

As the solar module can be considered a large diode, it does present diode characteristics. The behavior of the module described by the I-V curve can be defined as a plot of the Shockley diode equation that takes in account additional parameters of the module such as the ideality factor n and saturation current I_0. [13]

$$I = I_L - I_0 \cdot \left(e^{\frac{q \cdot (V + I \cdot R_S)}{nkT}} - 1\right) - \frac{V + I \cdot R_S}{R_{SH}} \quad (5)$$

Measuring the value of the ideality factor is a good way to assess the quality of the module as well as any defects in may present. Ideality factors of silica based modules should have values be between 1 and 2, the value 1 would describe an ideal diode so the ideality factor of a module will always be above 1 but there can be cases when ideality factors can have values larger than 2 and can even go up to 4 or 5. Such large ideality factor values would describe a module that has damaged solar cells. That damage may consist of scratches or other flaws on the surface of the module caused by weather phenomena, such defects may lead to unusual recombination of the charge carriers that will drastically reduce the efficiency and the energetic output of the module. [14]

Measuring the ideality factor of the module can be a hard task especially if a good accuracy is required. Usually, the ideality factor is measured by tracing a dark I-V curve. This method involves injections of charge carriers into the module. This process requires expensive equipment and can be dangerous for the module if the quantity of carriers is too large as it might destroy the cells within the module. An alternative that yields a lower precision but is less expensive to implement is given by the use of different levels of lighting to evaluate the ideality factor. This involves the use of a projector or any other artificial light source that can assure a constant light intensity and by varying the illumination levels (by using a mesh or by increasing the distance between the module and the light source) an approximate value of the ideality factor can be achieved. This method requires measurements of the short circuit current and the open circuit voltage at the various illumination levels and plotting those values on a graphic taking in account that the current intensity must be placed on the ordinate axis as a natural logarithm. For low current solar modules, the natural logarithm of the short circuit current will give a negative value but that will not pose a problem as the slope of that graphic is the only value required. Once the slope has been calculated the following formula will give the value of the ideality factor [15]:

$$n = \frac{\frac{q}{kT}}{m} \qquad (6)$$

In this equation q/kT is the inverse of the thermal voltage and m is the slope of the graphic. In addition to the measurement of the ideality factor, this method also allows the calculation of the saturation current I_0. This can be achieved by calculating the y-intercept of the graph that has been plotted, this value is equivalent to the point where the graph intersects the y-axis and it can be computed in any statistical application. Once the intercept has been calculated the saturation current can be calculated as follows:

$$I_0 = e^{y\_intercept} \ (7)$$

The saturation current is related to the influence of temperature on the voltage so knowing the value of this parameter is essential to assess the behavior of the module at high temperatures, as high values of this current lead to a great impact of the temperature on the voltage. [16]

3. EXPERIMENTS AND RESULTS

In order to conduct the measurements on the module all sensors had to be connected to the microcontroller. The schematic of that assembly can be seen in the following images:

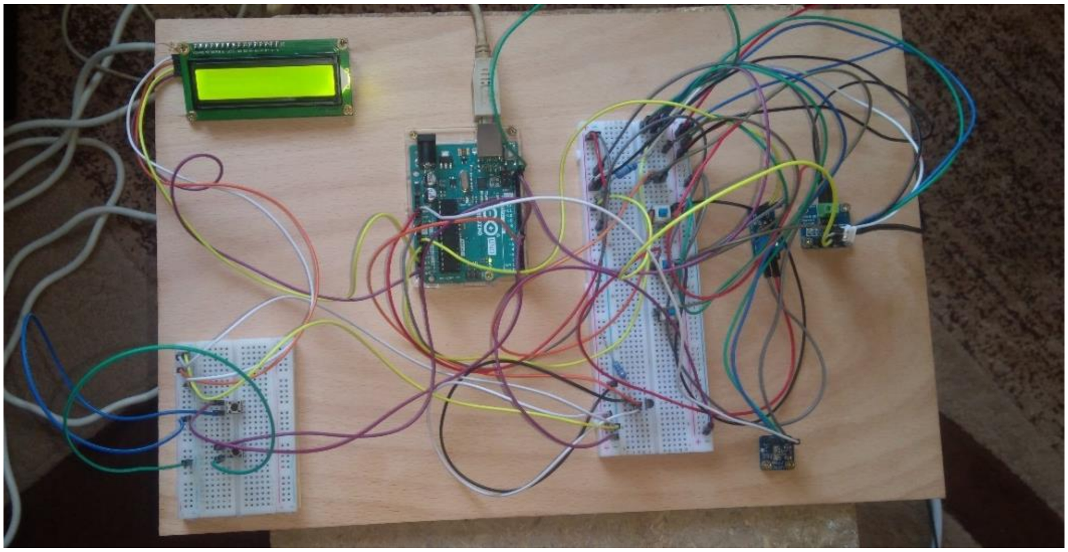

Figure 2. Assembly of the sensors

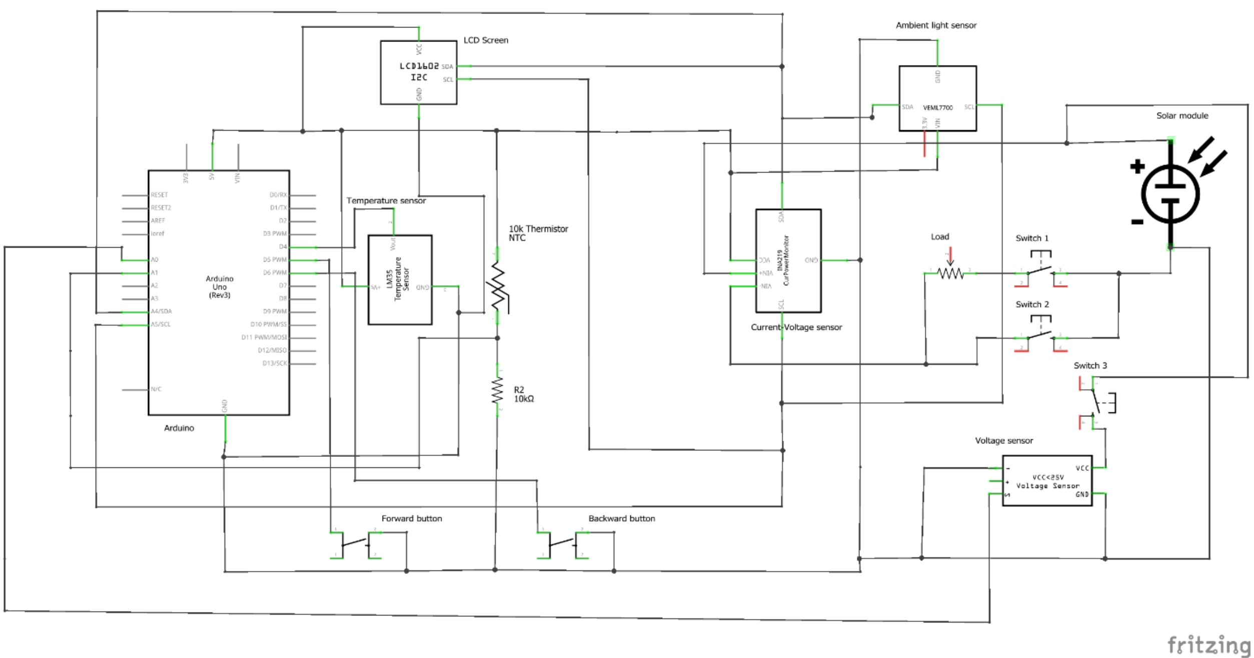

Figure 3. Schematic of the assembly

The sensors are connected to the microcontroller through a breadboard, a solderless protoboard that allows easy connections through jumper wires. The usefulness of a breadboard in the case of measurements conducted on low current solar modules is given by the possibility of changing the load resistors very fast when tracing an I-V curve in low light conditions. In this study the I-V curve of the solar panel has been traced under natural light that had a very low intensity. The measurements were conducted at the winter solstice, under the presence of clouds. At the time of the measurement the solar irradiance had a value of around 20 W/m^2, value estimated with equation 2. Also, the temperature was close to 0 ºC so it had no impact on the output of the module. The I-V and P-V (power-voltage) curves obtained can be seen in the following figure:

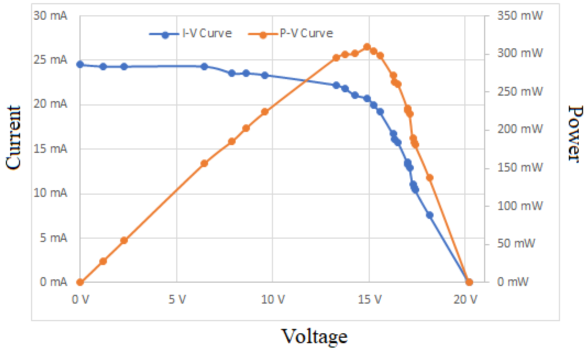

Figure 4: Measured I-V and P-V curves of the solar module at low light conditions

In the following table the parameters that were directly measured with the microcontroller are compared to the ones obtained at Standard Test Conditions (STC)

Table 1. Measured parameters compared to the STC parameters specified by the manufacturer

	Low light conditions	STC
Open circuit voltage (V_{oc})	20.2 V	21.6 V
Short circuit current (I_{sc})	24.5 mA	1.18 A
Maximum power (P_{max})	308.9 mW	20 W
Maximum voltage (V_{max})	14.9 V	18 V
Maximum current (I_{max})	20.7 mA	1.11 A
Characteristic resistance (R_{ch})	720 Ω	16.2 Ω

As it can be observed, the large values of the resistances needed to plot the current-voltage characteristic do not allow the use of an adjustable rheostat so the manual change of the resistors was needed, but the breadboard was an easy solution to this problem as the measurement could be conducted before the ambient light conditions changed.

Table 2. Other parameters that were calculated based on the measured parameters

	Low light conditions	STC
Fill factor (F)	61.20%	73.07%
Efficiency (η)	10.81%	14.28%
Series resistance (R_s)	13.43 Ω	N/A
Shunt resistance (R_{sh})	50.2 kΩ	N/A

The series resistance was the only parameter that could not be measured at the current conditions because the currents were so low that the sensor could not record them, but a measurement of the slope near the open circuit voltage point at a higher irradiance level can give the value of this parasitic resistance as it varies very little with the irradiance level.

In addition to the measurement of the I-V characteristic under low light condition, the measurement of the ideality factor was also successfully achieved by using a light projector equipped with a 500 W halogen light bulb. Six samples of the short circuit current and open circuit voltage were taken by varying the distance between the projector and the module taking in account that the angle under which the light hits the surface of the module has to remain the same. The distance was increased by 10 cm at each sample starting from 20 cm up to 70 cm.

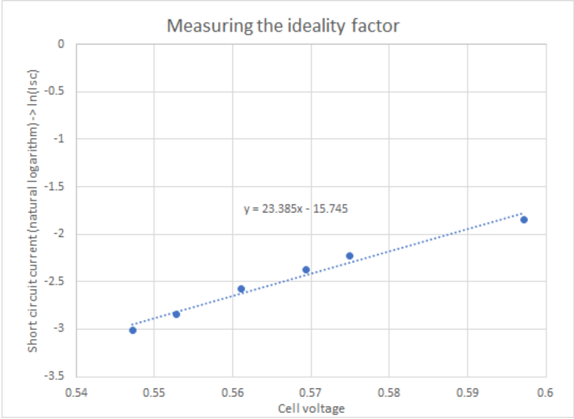

Figure 5: Obtaining the slope needed for the calculation of the ideality factor

In this case it must be mentioned that that only the cell's open circuit voltage is relevant so in the case of measurements conducted on a module the voltage on the x-axis must be divided by the number of cells in the module, in this study the module used had 36 cells. The results give the slope of the graphic that is equal to 23.385 and the y-intercept with the value of -15.745. The ideality factor can be calculated with equation (6) and the saturation current can be calculated by raising the Euler number to a power equal to the y-intercept $I_0 = e^{-15.745}$ thus obtaining the following values:

Table 3. Values for the ideality factor and saturation current

Ideality factor (n)	1.65
Saturation current (I_0)	$1.4\cdot10^{-7}$ A

The photocurrent also known as I_L is the only parameter that is not measured but it is usually considered as being equal to the short circuit current as long as the module doesn't have a particularly large series resistance.

The evolution of the module and ambient temperatures as well as the illumination level could also be successfully measured by taking samples at every 5 seconds.

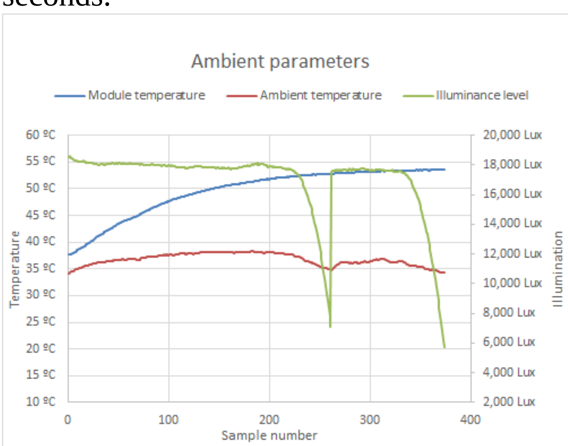

Figure 6. Measurement of the ambient parameters that are influencing the output of the module

CONCLUSIONS

Using a microcontroller to measure the parameters of a solar module can prove to be an advantageous solution for low-cost assessments of the module's efficiency and behavior. The sensors can measure any type of module under any kind of conditions as long as it does not exceed the current and voltage limitations of the sensors. In this study, the sensors could not measure currents higher than 3.2 A and voltages higher than 25 V.

At the time of the measurements the microcontroller was connected to a computer through a USB port but the use of an LCD screen can display the parameters even if there is no access to a computer. Displaying multiple parameters can be an easy task if an interface consisting of forward and backward buttons is implemented.

The user-friendly programming environment of Arduino that is based on the C++ language provides an easy way to implement the methods mentioned in this paper into the microcontroller and the I2C interface of the sensors and the LCD display prevents the user from dealing with a complicated schematic that would require additional components.

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