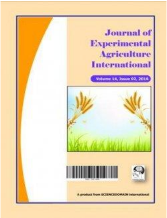

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Elaboration of an Open Source Prototyping Platform for Salubrity Monitoring in Agricultural Machinery

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Authors' contributions

This work was carried out in collaboration between all authors. Author FFLS did the prototype design and coding, also the writing and editing. Author FCS wrote the protocol and performed the statistical analysis. Authors LFLS and RNM did the prototype assembling and data analysis. Authors GMA and LCMT collected the data and managed the literature searches. All authors read and approved the final manuscript.

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ABSTRACT

Agricultural operations are generally carried out in places subject to abrupt environmental changes. In order to provide improvements in the work environment of tractor operators, it is of the utmost importance to monitor and make changes in the work environment. The present work aims to elaborate a low cost, flexible and easy to handle prototype, geared towards monitoring some parameters associated with the salubrity conditions of the agricultural tractor operator's working environment, which are: sound pressure level, ambient temperature and relative air humidity. The developed prototype acquire data through low-cost sensors and interprets the analyzed parameters comparing their values to those recommended by the Brazilian Regulatory Standards 15 (Unhealthy Operations and Activities) and 17 (Ergonomics), in order to perform a salubrity analysis of the local

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environmental conditions and to issue visual alerts to the operator when any parameter is outside the range of interest. Industrial reference equipment, such as a decibel meter and a thermo hygrometer, were used in order to calibrate the sensors, which are responsible for monitoring the above-mentioned parameters. For purposes of precision evaluation, the data acquired by both systems (sensors and the reference equipment) were subjected to the Tukey test at a 5% significance level ($P < 0.05$). It was concluded that the elaborated prototype is effective to monitor cab temperature, relative air humidity and noise level. Also, it has potential for deepening in the monitoring of continuous and intermittent noise and calculation of the dose of noise on the operator throughout his/her working day. In addition, the prototype proved to be successful due to its low-cost (88.6USD), fast data acquisition, flexibility and relatively simple assembly and operating methodology. The prototype's code is available in the GitHub platform.

Keywords: Arduino; safety at work; agricultural tractor; sensors.

1. INTRODUCTION

Brazil is one of the world leaders in the production and export of agricultural products [1], where agricultural machinery and implements are essential for much of the economic and technological boost observed in the field [2]. The agricultural tractor plays a key role for the agricultural workers, being an important tool to assist in the work, making it more practical and fast [3]. However, the operator is constantly subjected to physical and mental stresses when operating the tractor [4].

There are numerous risk factors that can cause these stresses to operators, among which two groups stand out: a) Pressures of physical agents such as noise, heat, vibrations and radiations and b) Pressures of chemical agents such as dust and gases [5,6]. Several studies [7, 8,9], indicate that the most common types of injuries and withdrawals among tractor operators are physical accidents, usually caused when operators are subjected to situations of discomfort and stress. Therefore, it is necessary to monitor some parameters that are associated with risk factors, such as: ambient temperature, relative air humidity and sound pressure [10,11].

In modern tractors, systems that monitor the conditions of the tractor's cabin already exist, in some models the system itself is built inside the cabin; however these systems represent a high cost for the customer. Aiming to evaluate the working conditions inside the tractor's cabin [12, 13,14] utilized a decibel meter to measure noise level. However, this equipment requires prior knowledge for its operation, and do not allow automation of monitoring and have a considerably high acquisition cost. In addition, [5] evaluated two different tractor brands to measure the noise level and thermal load to which an operator is subjected. However the equipment utilized for [5] presented the same financial and technical disadvantages to the studies cited above.

In this scenario, the use of microcontrollers (small computer in a single integrated circuit used for automation of tasks) appears as an option of both low cost and ease of use of application for the automation process of data monitoring [15]. Kunjumon et al. [16] designed a temperature, humidity monitoring and alert system, based on the integration of a microcontroller with a temperature and humidity sensor, with potencial to automate the ergonomic monitoring of a working station. In another study, Dener [17] proposes a system for ambient monitoring applications, consisting of a microcontroller board, a wireless communication system, temperature, humidity, water level and sound amplitude sensors, obtaining as result of a flexible and low-cost human health monitoring system. However, there is still no works in the literature that mention the use of low-cost sensors to perform the monitoring of salubrity conditions in a tractor cab.

Thus, the present work aims at the elaboration of a low cost, flexible and easy to handle prototype, in order to monitor the worker's health conditions. The prototype should be able to issue visual alerts to the operator when any parameter is outside the range of interest.

2. MATERIALS AND METHODS

2.1 Experimental Site

The work was carried out at the Fluminense Federal University, Niterói - Brazil, in the Laboratory of Agricultural Machinery (LABMAQ), place in which the assembly, testing and data collection phases of the prototype were performed. The measurements of the parameters were carried out on two distinct days, in order to evaluate the influence of different climatic conditions on the performance of the developed platform.

2.2 Legal Substantiation

The device should be able to interpret the value of the parameters measured by the sensors and compare them to the values recommended by the Regulatory Standards 15 and 17 [18, 19] on unhealthy activities and operations, and ergonomics, respectively. To this end, the following recommendations were adopted:

- Cab temperature should vary between 20 °C and 23 °C;
- Relative air humidity should not be less than 40%;
- Maximum noise level should not exceed 85 dB(A) (considering a working day equivalent to 8 hours).

2.3 Materials

2.3.1 Tractor

The tractor used in the experiment was an Agrale model 4100. This model has an aspirated engine with power equal to 14.7 hp, displacement of 668 cm³ (single cylinder), traction only in the rear wheels (4x2), and maximum torque equal to 39 N.m (at 2350 rpm).

2.3.2 Microcontroller

In order to perform the monitoring of physical parameters, such as temperature, relative air humidity and noise level, several authors [20, 21, 22] adopted the Arduino UNO® as a microcontroller board model to be used. This model features an ATmega328 microcontroller chip, operating voltage of 5 V, 14 data input/output digital pins, 6 input/output data analog pins, a 16MHz quartz crystal (responsible for controlling the precise synchronization of processors) and flash memory equal to 32 KB (memory for data storage).

The programming routine to be executed in the controller is accomplished through the IDE (Integrated Development Environment), which is a free software based on the programming language C. This software allows a set of instructions to be written in a personal computer, and later loaded to the controller [23].

2.3.3 Sensors and data collection

In order to monitor the ambient temperature and relative air humidity, the AM2302/DHT22® sensor (Aosong Electronics Company) was adopted. This sensor has a 3.3 V or 5 V supply voltage and ts accuracy is ± 0.5 ºC and ± 2% (ambient temperature and relative humidity, respectively). Regarding the sound pressure level monitoring, the Sparkfun Sound Detector® sensor was used. This sensor informs the ambient sound amplitude’s analog signal. It has a supply voltage equal to 3.3 V or 5 V and allows a sensitivity adjustment by means of an internal resistance that is coupled to the module and can vary to adjust the gain of the value (in volts) in its pre-amplifier.

Scarpa et al. [24] and Martin-Garín et al. [25], recommend the use of the AM2302/DHT22® sensor (Aosong Electronics Company) to monitor ambient temperature and relative air humidity conditions in a variety of applications. According to Shaker & Imran [26], this sensor has fast response, good accuracy and high resolution. Gang et al. [27] report that the module is capable of transmitting data over more than 20 meters.

The sensors’ data were recorded directly on an external memory card, in such a way that an external computer was not required during the entire data collection period. Thus, the storage of the collected data was carried out by an SD Card module integrated to a micro SD card with storage memory equal to 8 GB. Other authors have also opted for this recording method [28]. The module features an operating voltage of 3.3 or 5 V and supports FAT16 and FAT32 file formats (Standard file system on SD cards).

In addition, the system has an RTC module, a breaker switch and an RGB LED (light emitting diode that emits red, green or blue colors). The breaker switch is responsible for initiating and interrupting the data recording on the micro SD card, being a function of its position (on/off). Depending on the data recording status, the RGB LED will change its color to green if the data is being recorded, and to red if the recording is interrupted. Moreover, the RTC DS3231 module acts as a real-time and high-precision clock, making it possible to note the time when a given data was generated, which makes it easier to manage the monitoring process.

The real-time Visual Alert System is composed by three LEDs and an LCD display, RT162-7 model, which informs the operator in real-time values measured by the sensors. The LEDs integrated into the circuit are responsible for alerting the operator if the analyzed parameters are within the pre-established range. Each of the LEDs is responsible for a different parameter. They remain "on" according to the following conditions:

- Relative air humidity smaller than 40% (green LED);
- Temperature below 20 °C or above 23 °C (yellow LED);
- Noise level greater than 85 dB(A) (red LED).

Finally, the prototype circuit is shown in Fig. 1.

2.3.4 Reference equipment

A digital thermo-hygrometer, model Incoterm® 7666.02.0.00, was used to obtain reference data of relative air humidity and ambient temperature. This equipment has an accuracy of ± 1 °C/°F for internal or external temperature and ±0.5% for relative air humidity. In order to obtain the sound pressure reference data, a digital decibel meter, model Instrutherm® DEC-490 was used. This model has an accuracy of ± 1.4 dB(A) and is factory calibrated. Also, it was configured to operate in the 50-100 dB measuring range, which is typically the range in which tractor's noises are found, in the "A" and slow response compensation circuits, as provided in Regulatory Standard 15 [18], for the measurement of continuous or intermittent noise levels.

2.4 Experimental Procedures

During the experiment, the tractor remained static and the engine was switched on during the data collection period at the following rotating speeds: 1000, 1500, 2000 and 2500 rpm. Next, for data collection and prototype testing purposes, the sound pressure sensor together with a metal bracket were installed near the tractor seat and fixed at the operator's ear height, as recommended by Minette et al. [10]. To perform data collection, the decibel meter was positioned in the same location as the sound pressure sensor. Furthermore, the relative air humidity and temperature sensor as well as the thermo-hygrometer probe were positioned side by side and installed in the tractor seat.

The microcontroller together with the data collection system were installed in a MDF wooden box, to avoid mechanical damage and direct contact of the circuit with dust and humidity. The box was fixed to the tractor seat. Similarly, the real-time visual alert system was installed in another MDF wooden box; however, it was positioned on the tractor's panel.

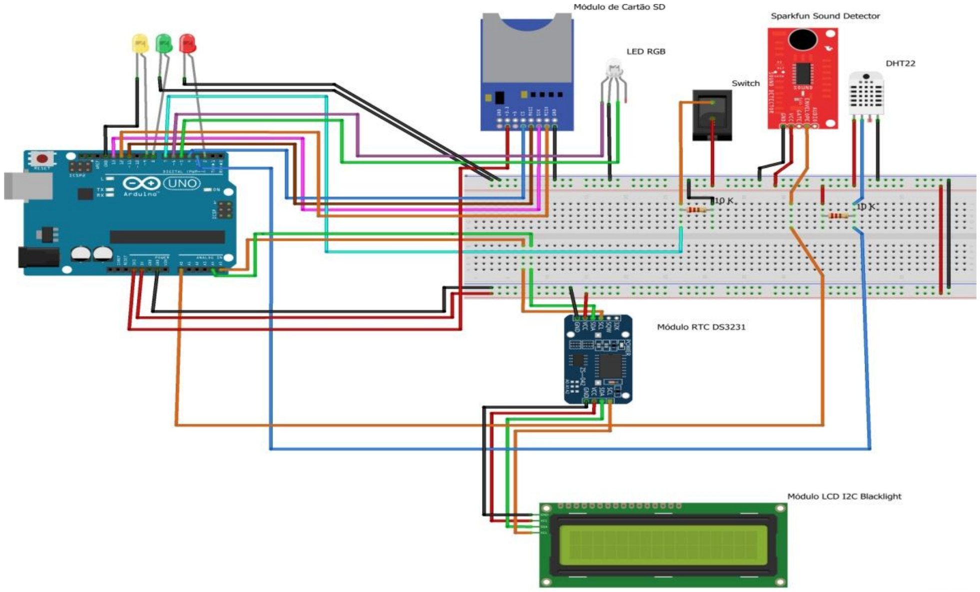

Fig. 1. Layout of the prototype's electronic circuit

In order to store the results, two different datasets were created: one consisting of the measurements obtained by the sensors and the other composed by the measurements obtained by the reference instruments. A data collection period of 5 minutes was set for each of the engine operating speeds (1000, 1500, 2000 and 2500 rpm). For the first database, the values obtained by the sensors were recorded on the micro SD card with an interval of 5 seconds between the recordings. For the second database, with the aid of a stopwatch, the measurements of the thermo-hygrometer and the decibel meter were recorded with intervals of 15 seconds between measurements.

To ease the comparison between the data measured by the sensors and the reference equipment, averages of the sensors data were calculated every 3 sequential repetitions (matching the amount of data collected by the reference equipment). The comparison between the results obtained by the sensors and the reference equipment was established through the Tukey test at a 5% significance level ($P < 0.05$). In this sense, if the data obtained by the sensors present statistical difference when compared to the values provided by the reference equipment, it is necessary to elaborate a calibration curve for the sensors.

2.5 Sensors Calibration and Validation

If the ambient temperature and relative air humidity data collected by the AM2302/DHT22® sensor present a statistically significant difference when compared to the values collected by the thermo-hygrometer, two different calibration curves should be adjusted.

The first curve refers to the ambient temperature (equation 1), and the other to the relative air humidity data (equation 2). Both curves will be defined by mathematical regression and will be of the following format:

$$T = f_1(T_0) \tag{1}$$

$$U = f_2(U_0) \tag{2}$$

Where:

T = Ambient temperature (ºC);
f_1 = Function defined by calibration;
T_0 = Initial temperature value estimated by the sensor;
U = Relative air humidity (%);
f_2 = Function defined by calibration;
U_0 = Initial relative air humidity value estimated by the sensor.

The Sparkfun Sound Detector® sensor provides sound amplitude values in the analog port, and a calibration is required to obtain sound intensity values, in decibels.

Sensor output values and decibel meter measurements were collected for seven different sound intensities in the range of 43.50 – 90.0 db(A), over a period of 30 seconds. For each measurement there were three replicates. After a data filtering according to the mean values obtained and the actual reference values, a calibration curve was set for the sound pressure sensor defined by mathematical regression (equation 3).

$$P = f_3(V) \tag{3}$$

Where:

P = Ambient sound intensity, dB(A);
f_3= Function defined by calibration;
V = Voltage produced by the sound pressure sensor (mV);

The noises were generated by continuous noise sources such as: blender, vegetable mixer, vacuum cleaner and surround sound in an enclosed room.

In order to validate the calibration of the sensors (if necessary), the coefficient of determination (R^2) of the curve should be used. The validation was performed based on the highest value of R^2.

In order to estimate the standard error of the prototype's sound pressure sensor, the error was calculated for each individual measurement collected in the field (equation 4). The standard error of the noise level sensor was taken as the standard deviation of the mean of the measurements, and can be calculated by equation 5:

$$E = ABS(V_s - V_d) \tag{4}$$

Where:

E = Error of each individual measurement dB(A);
ABS = Absolute value of a mathematical operation;
V_s = Calibrated output value of the sensor;
V_d = Value obtained by the decibel meter, dB(A).

$$S_x = s/\sqrt{n} \quad (5)$$

Where:

S_x = Standard error of prototype's sound pressure sensor dB(A);
S = Sample standard deviation, dB(A);
n = Size of the sample.

The standard error for the temperature and relative air humidity was already informed by the sensor's manufacturer and is specified in the section 2.3.3.

3. RESULTS AND DISCUSSION

The prototype's code is available in the GitHub platform and can be accessed through the link: "https://github.com/FernandoFSantos/arduino-projects/blob/master/Projeto_MONIT-TRACTOR.ino"

3.1 Statistical Analysis of the Data

3.1.1 Ambient temperature and relative air humidity

Table 1 presents the result of the Tukey test for the ambient temperature parameter, for both days of data collection.

It can be seen in Table 1 that the averages of ambient temperature data, obtained experimentally by the sensor and the Thermo-hygrometer are statistically different at a 5% significance level from each other for both days of data collection, considering all engine rotational speeds.

The Table 2 presents the result of the Tukey test for the parameter of relative air humidity, for both days of data collection.

It can be verified in Table 2 that the averages of relative air humidity data, obtained experimentally from the sensor and the Thermo-hygrometer are statistically different from each other for both days of data collection, considering all engine rotational speeds.

Thapliyal & Kumar [29] used the same sensor of the present time of work in order to develop a system of real time parameter monitoring and motion detection for critical/restricted compartments, on marine platforms with data logging capability. It was reported that data acquired from DHT22 presented a standard error of 0.8% for temperature and 1.5% for relative air humidity. Therefore, authors needed to calibrate the system in order to acquire more accurate data.

Table 1. Averages of ambient temperature (ºC) by Tukey test collected for both days using different engine rotational speed (rpm)

Engine rotational speed(rpm)	Day 1		Day 2	
	Equipment			
	DHT22 sensor	Thermo-hygrometer	DHT22 sensor	Thermo-hygrometer
1000	23.48 ^{a}	24.45 ^{b}	21.95 ^{c}	22.97 ^{d}
1500	23.43 ^{a}	24.39 ^{b}	21.76 ^{c}	22.71 ^{d}
2000	23.31 ^{a}	24.35 ^{b}	21.66 ^{c}	22.57 ^{d}
2500	23.45 ^{a}	24.42 ^{b}	21.64 ^{c}	22.60 ^{d}

Means that do not share a letter in the same line are significantly different by Tukey's test (p<0.05)

Table 2. Averages of relative air humidity (%) by Tukey test collected for both days using different engine rotational speed (rpm)

Engine rotational speed (rpm)	Day 1		Day 2	
	Equipment			
	DHT22 sensor	Thermo-hygrometer	DHT22 sensor	Thermo-hygrometer
1000	57.17 ^{a}	61.00 ^{b}	77.36 ^{c}	82.30 ^{d}
1500	57.55 ^{a}	61.00 ^{b}	80.03 ^{c}	85.10 ^{d}
2000	58.49 ^{a}	62.00 ^{b}	80.82 ^{c}	86.05 ^{d}
2500	58.07 ^{a}	61.80 ^{b}	80.76 ^{c}	86.10 ^{d}

Means that do not share a letter in the same line are significantly different by Tukey's test (p<0.05)

Due to the sensor's lack of accuracy at the present work, calibration curves for the temperature and relative air humidity parameters were drawn, in order to enhance the sensor's performance.

3.1.2 Sound pressure

The Table 3 presents the result of the Tukey test for the parameter of sound pressure, for both days of data collection.

It can be analyzed in Table 3 that the averages of sound pressure data, obtained experimentally from the sound pressure sensor and the decibel meter are statistically equal only for the engine rotational speed [1] of 1500 rpm of day 1, considering a level of significance of 5%. In view of the previous results, there is the need to add an isolated microcontroller board for a circuit with the sound pressure sensor. Thus, the interference caused by the excess of data recording in the microcontroller on the reading of analog data of the sensor will be eliminated.

3.2 Sensor Calibration

By means of mathematical regression, using Microsoft Excel®, it was obtained a linear type calibration equation (equation 6) for the ambient temperature collected data.

$$t_f = 1.0979 \times t_0 - 1.2386 \qquad (6)$$

Where:

t_f = Calibrated output value of the sensor, in Celsius degrees;
t_0 = Uncalibrated value, in Celsius degrees.

The R^2 value obtained by the calibration curve, related to equation 5 was 0.982, indicating a good correlation between both variables, validating the calibration of the sensor. In similar studies, the authors also obtained a linear calibration curve when performing the calibration of the same sensor [30,31]. The first one calibrated the sensor in a Sugar Cane plantation area, obtaining as result a R^2 equal to 0.997. The second one obtained 0.999 when using the sensor to evaluate the efficacy of evaporative panels consisting of PET bottles.

Analogously, it was obtained a linear type calibration equation (equation 7) for the relative air humidity collected data.

$$u_f = 1.0233 \times u_0 + 2.782 \qquad (7)$$

Where:

u_f = Calibrated output value of the sensor, in percentage of relative air humidity;
u_0 = Uncalibrated value, in percentage of relative humidity.

The R^2 value obtained by the calibration curve, related to equation 6 was 0.990, indicating again a good correlation between both variables, validating this calibration. Other authors when working with the same sensor obtained similar results (R^2 equal to 0.995 and 0.999, respectively) [30, 31].

For the sound intensity collected data, it was obtained a logarithmic calibration (equation 8).

$$Y = 10.878 \times \ln(x) + 28.071 \qquad (8)$$

Where:

Y = Output value of the sensor, dB(A);
X = Analog output value of the sensor, in mV.

The value of R^2 obtained by the calibration curve was 0.922, indicating a high correlation between the values, validating the calibration of this sensor.

After calibrating the sound pressure sensor and testing it against field data it was observed a standard error of ±1.1 dB(A). Kardous & Shaw [32] found an error of ±2.0 dB(A) when measuring sound level with several iOS apps in the range of 65 to 95 dB(A). In the other hand, Murphy & King [33] investigated the standard error of 100 mobile phones (different models and operating systems) and found an error or ±2.93 dB(A) for iOS devices and ±2.79 dB(A) for Android devices. Authors concluded that smart phones are not ready to replace sound level meters. Finally, Muto et al. [34] developed an automatic calibration system of a sound level meter using a microcomputer and reported an error of ±3.0 dB(A). Therefore, considering literature and the low cost of the sensor, the standard error of ±1.1 dB(A) found for the sensor calibration is considered quite acceptable.

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[1] *engine rotational speed*

Table 3. Averages of sound pressure (dBA) by Tukey test collected for both days using different engine rotational speed (rpm)

Engine rotational speed (rpm)	Day 1		Day 2	
	Equipment			
	Sound pressure sensor	Decibel meter	Sound pressure sensor	Decibel meter
1000	80.42 ^{a}	81.22 ^{b}	75.43 ^{c}	83.88 ^{d}
1500	86.01 ^{a}	86.23 ^{a}	78.92 ^{c}	86.70 ^{d}
2000	84.42 ^{a}	89.56 ^{b}	83.23 ^{c}	88.45 ^{d}
2500	83.93 ^{a}	90.67 ^{b}	86.50 ^{c}	89.03 ^{d}

Means that do not share a letter in the same line are significantly different by Tukey's test (p<0.05)

4. CONCLUSION

Through the statistical analysis of the data it was concluded that the averages of the sensors and of the reference equipment were statistically different from each other. Therefore, it was necessary to elaborate calibration curves, in order to calibrate all the sensors used to build the prototype. The standard error for the calibration of the sound pressure level sensor was ±1.1 dB(A), which is quite acceptable.

For the salubrity analysis and monitoring of the developed activity, the elaborated prototype proved to be effective and with potential for deepening in the monitoring of continuous and intermittent noise and calculation of the dose of noise on the operator throughout his/her working day. Also, the prototype proved to be successful due to its low-cost (88.6USD), fast data acquisition, flexibility and relatively simple assembly and operating methodology. The prototype’s code is available in the GitHub platform.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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