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Development of a Low-Cost Particulate Matter Optical Sensor for Real Time Monitoring †

Martín Aarón Sánchez-Barajas [1], Daniel Cuevas-González [1,*], Marco A. Reyna [1,*], Juan C. Delgado-Torres [2], Eladio Altamira-Colado [1] and Roberto López-Avitia [2]

[1] Instituto de Ingeniería, Universidad Autónoma de Baja California, Mexicali 21280, Mexico; martin.aaron.sanchez.barajas@uabc.edu.mx (M.A.S.-B.); ealtamira@uabc.edu.mx (E.A.-C.)
[2] Facultad de Ingeniería, Universidad Autónoma de Baja California, Mexicali 21280, Mexico; juan.delgado5@uabc.edu.mx (J.C.D.-T.); ravitia@uabc.edu.mx (R.L.-A.);
* Correspondence: cuevas.daniel@uabc.edu.mx (D.C.-G.); mreyna@uabc.edu.mx (M.A.R.)
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Abstract: Air pollution is a critical public health problem that has increased during the last decades. High levels of air pollution have affected natural environments and people's health, causing significant problems and, in severe cases, premature death. A growing trend called "Personal air monitoring", has become important for prevention and reduction of exposure to air pollutants. The development of personal particulate matter sensors is still a topic of study among the scientific community. Some important identified challenges are improving sample rate, precision, stability, dimensions and costs, making personal monitoring of air quality affordable. This work proposes the development of a low-cost particulate matter optical sensor to count the number of particles in real time using the Arduino platform and wireless transmission. Our results demonstrated that using a digital input of the microcontroller instead of the analog-digital converter, after conditioning the sensor signal, allows a very high max particle count, which can be compared to that of expensive sensors. In addition, particulate matter (PM) measurements were compared with a GP2Y1014AU0F dust sensor to validate the accuracy of the sensor.

Keywords: PM counter; personal air monitoring; low-cost sensor; air pollution monitoring

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1. Introduction

Air pollution is a critical public health problem that has increased during the last decades. There are natural sources of air pollution such as natural fires, volcanoes, and earth storms. However, anthropological activities such as burning fossil fuels, excessive use of transportation, and generation of electricity and household pollution have significantly aggravated the problem [1]. The most commonly encountered air pollutants are particulate matter (PM), ozone (O_3), sulfur dioxide (SO_2), nitrogen oxides (NO_x), carbon monoxide (CO) and lead [2]. Exposure to high levels of air pollution have affected natural environments and people's health, causing significant problems and, in severe cases, premature death. In 2019 the World Health Organization (WHO) estimated about 6.9 million deaths associated with air pollution [3]. A growing trend called "Personal air monitoring", has become important for prevention and reduction of exposure to air pollutants. The development of personal sensors for particulate matter is still a topic of study among the scientific community. There are low-cost, portable and low power consumption optical particle counter (OPC) devices on the market such as those mentioned in [4–7], as well as low-cost and miniaturized devices developed in the studies of [8,9] that use a laser diode and a photodiode for particle counting through light scattering. Particle counting may, depending on the study, be limited to the sample-throughput capability of the ADC converter or the digital stage of the microcontroller. In [4], the commercial OPC-N2 device from Alphasense has a maximum particle count of 10,000 particles per second, unlike the studies in [5–8] where the particle count per second is not mentioned. In [10] they developed a prototype to monitor the pollution levels in the environment using the optical dust sensor GP2Y1010AU0F as a basis for its development. In [11], the optical dust sensor GP2Y1010AU0F was used to analyze the correlation between the sensor drift and the accumulated production in a steel factory. Finally, in [12,13] they comprehensively analyzed and graphed the optical dust sensor GP2Y1010AU0F.

This work develop a low-cost particulate matter optical sensor that implements a digital counter to measure the number of particles in real time using the Arduino platform and transmit the information wirelessly (see Figure 1).

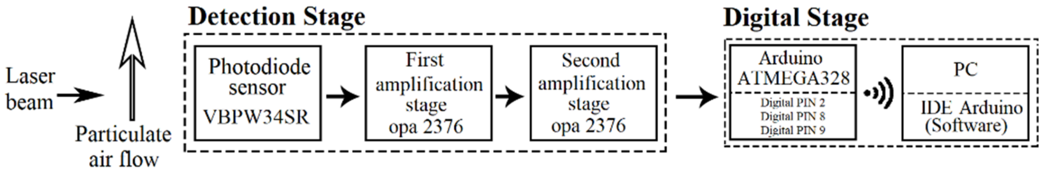

Figure 1. Diagram of the particulate matter optical sensor.

2. Materials and Methods

This paper presents the methodology to perform a low-cost PM sensor to count the number of particles in real time using the Arduino platform and wireless transmission.

2.1. Optical Sensor Operation

The circuit uses the principle of light scattering employing a laser beam and a photodiode that detects the variations that generate the flow of PM. These small variations are amplified and filtered by three stages (See Figure 2). The variations in an analog signal that can be measured on an oscilloscope or quantified by a digital system using a microcontroller.

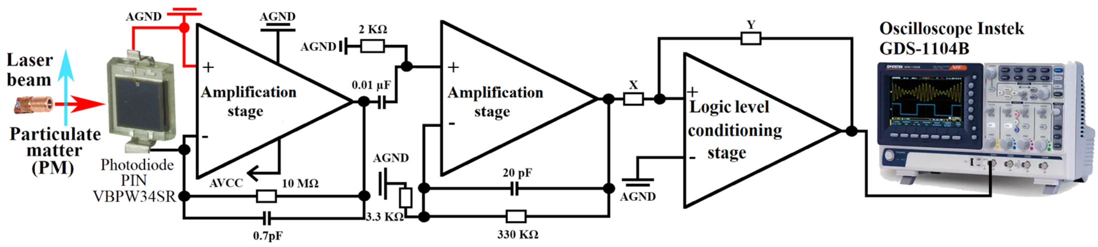

Figure 2. Circuit of the optical stage of the particulate matter sensor.

2.2. Printed Circuit Board (PCB) and Optical Stage Chambers

The circuit shown in Figure 2 was initially implemented on a breadboard; however, because the circuit is very sensitive to noise, a PCB was designed using DipTrace software (see Figure 3A,B) to avoid the noise captured by the breadboard. Subsequently, two chambers were designed using SolidWorks software to avoid noise produced by light from the environment (see Figure 3C,D), a chamber with 9 × 9 mm dimensions and another of 3 × 3 mm to identify how the air flow and dimensions affect the system.

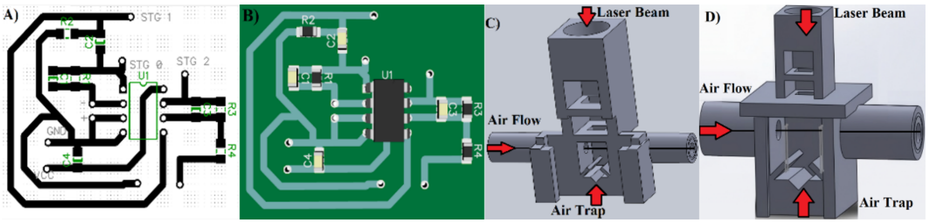

Figure 3. PCB and optical stage chambers designs. (**A**) PCB traces of optical stage and amplification, (**B**) 3D PCB design, (**C**) 3 × 3 mm PM flow chamber and (**D**) 9 × 9 mm PM flow chamber.

2.3. Digital Stage of the System—Pulse Counter

This stage presents the circuit design to count the pulses (digitization) of the analog signal due to the scattered light in particulate material, and then transmit via Bluetooth to a PC (See Figure 4). In order to determine the maximum number of particles that our device can count, it was necessary to generate a square wave with a 2.4Vp amplitude and frequencies from 60 Hz to 150 Hz with the GW Instek AFG-2225 function generator. (See Figure 4).

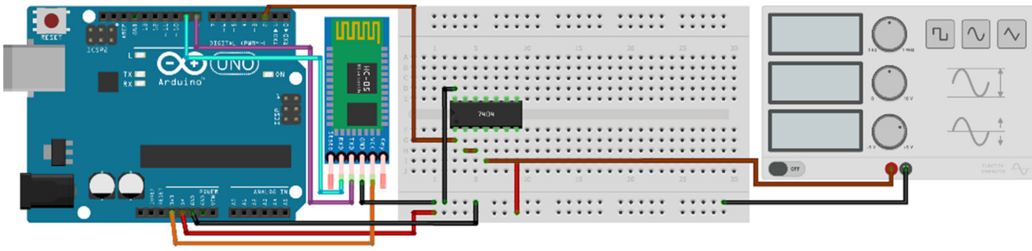

Figure 4. Digital stage validation circuit with Bluetooth transmission.

2.4. Operation of the Optical Sensor in the Chambers with Particle Counting

Once the optical circuit PCB has been independently evaluated on the oscilloscope, and validated the maximum operating limits of the pulse counter system and accuracy, a final test consists of performing these steps in conjunction with an exposure to smoke air flow and observing the particle count and compare it with a GP2Y1014AU0F dust sensor.

3. Results

3.1. Optical Sensor Operation

A visual comparison is shown in Figure 5 between the signal obtained using the GP2Y1014AU0F dust sensor and our developed low-cost PM sensor. Figure 5a is a graph found in the design guide of sensor TIDA-00378 from Texas Instruments that summarizes the relation between pulse heigh and particle size, as well as pulse spacing and particle concentration. Figure 5b shows the signal obtained from the GP2Y1014AU0F dust sensor, and Figure 5c shows the signal obtained from our developed low-cost PM sensor.

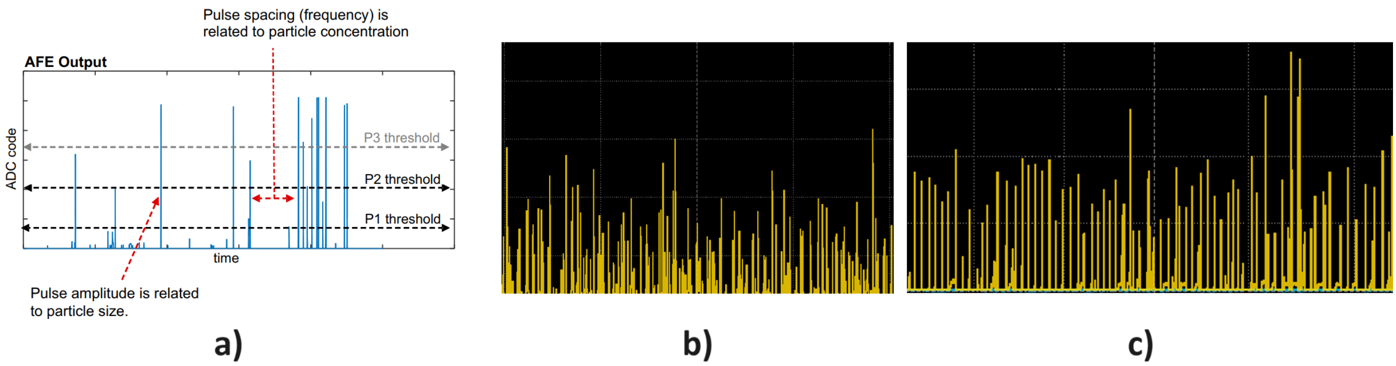

Figure 5. (**a**) Pulse amplitude and spacing relation with particle size and particle concentration. (**b**) GP2Y1014AU0F dust sensor output signal. (**c**) Developed low-cost PM sensor output signal.

3.2. Digital Stage of the System—Pulse Counter

To determine the maximum sampling frequency of the digital counter, tests were performed at different frequencies from 60 Hz–156.53 kHz with a baud rate of 1MB/s. It was calculated that the error for a frequency of 150 kHz is 0.06% and increases as the frequency increases, as shown in Table 1.

Table 1. Results of the digital pulse counter with its relative error percentage and its efficiency.

Frequency (Hz)	Theoretical Result	Measured Result	Relative Percentage Error (%)	Efficiency (%)
60	216,000	215,999	0.0004	99.99
1000	3,600,000	3,599,972	0.0007	99.99
10,000	36,000,000	35,989,777	0.0283	99.97
100,000	360,000,000	359,847,668	0.0423	99.95
150,000	540,000,000	539,654,597	0.0639	99.93
156,530	563,508,000	540,418,640	4.09	95.90

4. Discussion

A limitation of traditional particle counters is the microcontroller's analog-digital converter or external analog-digital converter, which carries out the particle counting of the analog stage. In our work, we used the Arduino platform's microcontroller which is limited to a 9.6 kHz frequency setting by default analog-digital converter to 10 bits. Therefore, to solve the limit in the sampling frequency of the analog digital converter, a digital reading alternative was implemented which registers particles with a maximum frequency of 150 kHz. Our proposal, instead of using the microcontroller's analog-digital converter, introduces the signal through a digital pin of the microcontroller to detect a high-voltage input that corresponds to a detected particle. Although for this method is necessary to implement a conditioning stage to ensure an appropriate logic level of the signal for the correct detection of particles as shown in Figure 2.

Another presented problem in the analog stage is that market-available devices have complex hardware, a complicated calibration, and they do not provide user support. Accuracy is a crucial parameter for pollutants measurement, therefore it is important that sensors are robustly validated and can be easily calibrated. In the work of [10] they found that the GP2Y1010AU0F sensor has calibration issues which can produce incorrect data while taking measures, as well as evidence that the sensor does not make homogeneous measures. While in [11] they mention that the manufacturer does not provide enough information about the sensor, which presents a problem when working with the sensor.

Finally, it was found in the digital stage after comparing our prototype with commercial devices, as shown in Table 2, that our prototype registers 150,000 particles per second with an accuracy of 99.93%, while commercial particle counters with a price of 50 USD or less can detect up to 1 000 to 40,000 particles per second, which represents an improvement of about 275%. Devices with higher particle count frequency (similar to our prototype) have a cost from 200 to 1000 USD approximately, while our prototype would cost less than 15 USD and considering a mass production the price could be around 8–10 USD. The limitations identified in our work are the test with the 9 × 9 mm chamber to identify how the air flow and dimensions affect the system, calibration tests with another robust commercial sensor, optimizing the code to increase the particle count in the digital stage, and performing statistics using the intraclass correlation coefficient (ICC).

Table 2. Specifications comparative of each sensor available on the market.

Sensor	Price (USD)	Release	Frequency (Hz)	Max. Particle Count
AirCasting AirBeam [14].	$250	2021	2	10,000
AirViz Speck [15].	$150	2022	2	10,000
AlphaSense OPC-N2 [16].	$1500	2020	10	100,000
Dylos DC1100/DC1100 Pro [17].	$260	2019	2	100,000
GP2Y1010A [18].	$10	2015	1	1,000
Nova PM2.5 [19].	$30	2021	1	10,000
PMS5003 [20].	$50	2017	2	20,000
PPD42NS [21].	$20	2022	2	10,000
Shinyei PMS-SYS-1 [22].	$1000	2021	2	100,000
TSI AirAssure [23].	$1000	2022	2	100,000
TZOA PM Research Sensor [24].	$600	2022	2	100,000
Our prototype	$14	2023	1	150,000

5. Conclusions

The development of personal monitoring sensors comprises important challenges such as improving sampling rate, precision, and stability without increasing the cost.

The analog signal conditioning and filtering stage is susceptible to noise, variability due to the angle of the laser/light source and the receiver, multiple amplifier stages can also cause variations. Developers of air personal monitoring must be careful to avoid these factors of variation and inaccurate readings. The analog-digital converters with high sampling rates increase the cost of a sensor significantly, therefore, using a digital counter for the digital stage, although it requires a more complex signal conditioning in the analog stage, is better to decrease costs and increase the sampling rate. As shown in the results, we obtained a particle count frequency (150 kHz) with a 14 USD cost.

As future work, some improvements are suggested such as increasing the particle count frequency in the analog stage, optimizing the code to increase the particle count in the digital stage, reducing the number of components, miniaturizing, and developing a communication interface for smart devices.

The development of new PM sensors, technology assimilation and cost reduction could make these sensors more accessible to prevent and reduce the exposition to air pollutants.

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