Understanding the Shinyei PPD42NS low-cost dust sensor

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Understanding the Shinyei PPD24NS low-cost dust sensor

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***Abstract*—Air quality measurement is a topic of a great interest for any country due to health and environmental reasons. Tis issue is more critical in low-incomes countries since the air quality is generally worse than in developed countries and the governments give fewer budget to lead environmental policy and research. This explains the increasing demand for low-cost dust optical sensors like the Shinyei PPD24NS during the last years. However, those sensors present mixed results in terms of precision and repeatability, especially in case of new applications like the ones in moving context. Moreover, few or confuse information exists on those sensors functioning and conditions of use and the manufacturer does not provide any comprehensive guideline. The present article aims at filling this gap, providing a real study of the internal sensor operating. This includes: a detailed, theoretical and practical, analysis of the electric diagram, a characterization of the airflow through the optical chamber, an output behavior analysis based on particulate matter concentration and some algorithmic issues guideline. The article ends by providing useful tips and recommendations as well as some tracks to improve its precision for new applications.**

Keywords: Air Quality, Optical sensors, Dust sensors, Particulate matter, Low-cost sensors.

I. Introduction

Air quality measurement is of a great interest for any country but for low-incomes countries this issue is more critical since the air quality is generally worse than in developed countries and the governments give fewer budget to lead environmental policy and research. For example, in Colombia, the 2017 Ministry of Environment budget was of about 0.3% of the total nation budget [1] while it was of 6% in France [2]. In those countries, investigations about air quality in urban cities and especially in public transport system [3] require accurate but inexpensive material in order to minimize risk of damaging or robbery. In parallel, many citizen initiatives about air quality monitoring like Air Casting (http://aircasting.org/) in USA, Air Citizen (http://aircitizen.org/) in France or SIATA (https://siata.gov.co/) in Colombia have born during the 5 ultimate years. This explains the increasing demand for low-cost dust sensors like the Shinyei PPD24NS. However, literature shows mixed results in terms of precision and repeatability for this kind of sensors: although some authors [4]–[7] showed a pretty good correlation between data from this kind of sensors and from some of the most common reference sensors like DustTrak (from TSI), DustMate (from Turnkey) or Dylos for long time dust exposure and static use, the sensor output is generally noisy or/and little accurate or /and non-linear for short time dust exposure and perturbed environments [6] or low particle concentration [7]. This, especially in case of new applications like the ones in moving context [8] leads to a poorer data accuracy or/and noisy signal, hence unusable data. In fact, few articles exist on those sensors functioning and condition of use. While some websites present deep and thorough work ([9], http://aqicn.org/sensor/) some others describe approximate and/or inexact functioning (http://aqicn.org/sensor/shinyei/http://

aqicn.org/sensor/shinyei/). However, many times users - including investigators - simply use electric diagrams and algorithms directly downloaded from those websites without any guidelines or guarantee about the information provided. Many of authors use data approximations based on linear regressions to get data from this kind of sensors and this works pretty well for some applications but due to the lack of a precise comprehension of the sensor operating, it is impossible to extend those results to a wider class of situations. This article aims at clarifying the functioning of this sensor and giving some tips and recommendation to improve its performance.

II. Dust sensors technologies

Three main kind of dust sensors exist in the market: gravimetric, mechanical and optical based principle. The optical technology seems to be widely used in various context due to its low cost. Nevertheless, each technology gives different information and each one should be considered according to the purpose of the study. The mechanical and gravimetric dust sensors for example measure directly the mass of dust particles in a given volume while the optical ones measure the amount of particle in a given volume. In this last case, user has to convert the "amount of particle" in a "mass of particle", which is an approximate calculus since it changes according to the nature of the particle (affecting mainly its reflection, density and hygroscopic characteristics). Sharp GP2Y1010AU0F, Shinyei PPD42NS and PPD60PV-T2, Syhitech DSM501A, Samyoung DSM501 and Amphenol/Telaire SM- PWM-01A are the most common used low-cost dust sensors. All work on the same optical scattering principle [8] but the Shinyei PPD24NS sensor seems to be even more used for its lowest cost (< 7 USD) and apparent ease of use.
Those sensors use a non-visible light wavelength produced by a "classical" light emitting diode while more precise and costly sensors use a red laser diode (Plantower PMS1003/3003/5003 for example) like in professional aerosol monitors.
The Koreans Syhitech DSM501A and Samyoung DSM501 are identical and they are copy of the Japanese Shinyei PPD42NS (in quite different packages). Those three sensors provide the same pulse width modulation output and have the same limitations.

III. The Shinyei PPD24NS sensor

Allen [10] wrote a reference technical document on this sensor and the present article aims at continuing that work. The Shinyei PPD42NS sensor (figure 1) is based on the optical detection of dust particles that pass through it, between a light source (a LED, Light Emitting Diode) and a detector, a photodiode (figure 2 from http://www.takingspace.org/make-your-own-aircasting-particle-monitor/).
Basically, dust particles modify the signal received by the detector from the light source by collecting the emitted light diffused by the dust particles (called "scattering" principle). A power resistor heats the air in the optical chamber and generates a flow between two apertures putted in the plastic cover.

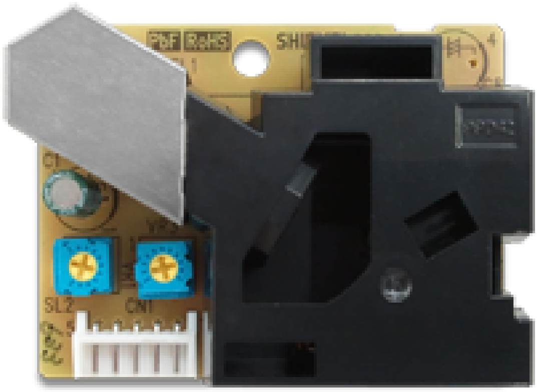

Figure 1. The PPD24NS sensor from Shinyei Technology Co. Ltd. (Notice the hole in center of the plastic cover that allows cleaning the lens.)

A. Electronic description

The internal diagram of the sensor drawn by Allen is showed in figure 3. It is composed of one detection circuit based on a couple of diode/photodiode following by two filters based on the general purpose operational amplifier (OAMP) NJR/NJM2902.
As mentioned in the cited document, dust particles modulate the current that passes through the photodiode and by the way the voltage at the point referenced TP16 (figure 3). Figure 4 shows this signal for small particle matter. As we can observe, the steady state of this signal is about 1.52 V, depending on the supply voltage (here, 4.66V), and changes

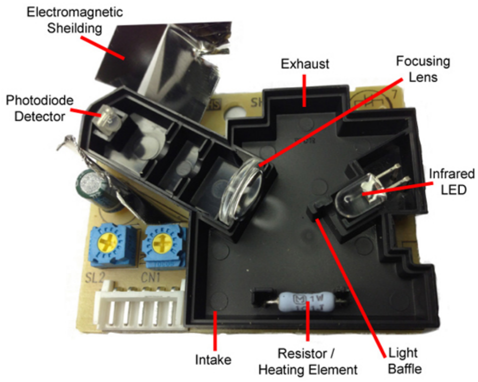

Figure 2. Internal components (from the HabitatMap & AirCasting Blog at www.takingspace.org).

positively when particles pass through the sensor.

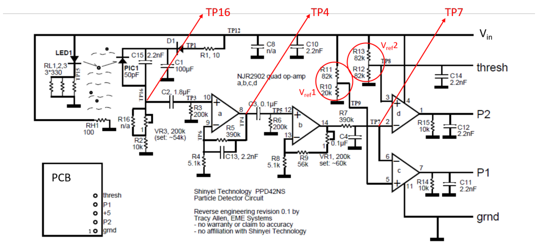

Figure 3. Diagram of the PPD24NS sensor from T. Allen, with test points location.

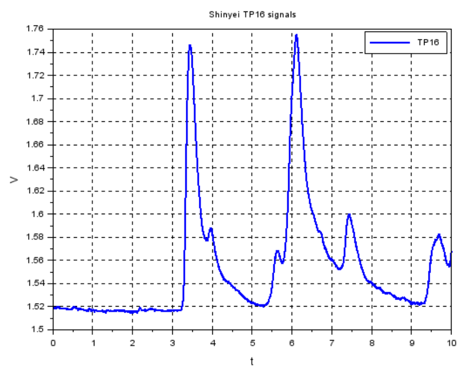

Figure 4. TP16 signal sample ($V_{ref} = 4.66V$).

Then the signal from the photodiode pass through 2 filters which transfer functions can be easily calculated [11]. The first one is a passive 1st-order high-pass filter (C2, R3) which cut the continuous voltage component from the first stage and more generally attenuates frequencies lower than 0.44Hz. The second filter is a 1st-order active low-pass one with a gain of 77.5 (37.7dB) in high frequencies (a cell, R4, R5, C13). Those two first filters combination gives a band-pass 1st-order filter which frequency response is showed in figure 5 and equation below:

$$F(s) = \frac{R_3C_2s}{1 + R_3C_2s}(1 + \frac{R_5}{R_4 + R_5R_4C_{13}s})$$

This filter attenuates the input signal below 0.052Hz and above 5000Hz approximately and gives its maximum gain around 10Hz.

The second stage is composed of a 1st-order high-pass cell (C3, R6) followed by an amplifier (b cell, R8, R9, VR1) and a low-pass filter (R7, C4). This gives a second band-pass 1st-order filter centered in 5.7Hz which frequency response is showed in figure 6 and equation is below:

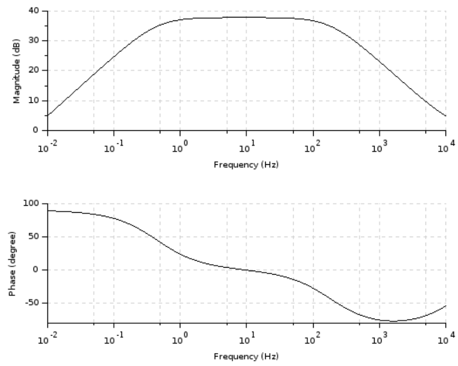

Figure 5. First filter frequency response.

$$H(s) = \frac{R_6C_3s}{1 + R_6C_3s}(1 + \frac{VR_1 + R_9}{R_8})\frac{1}{1 + R_7C_4s}$$

This filter attenuates frequencies below 0.34Hz and above 96.5Hz and gives a maximum gain of 8 (18.1dB). The combination of the first and second filter makes a 2nd-order band-pass filter which response is showed in figure 7. This filter gives a maximum gain of 616.6 (55.8dB) and a minimum phase shift at 5.7Hz, and attenuates frequencies lower than 0.135Hz and higher than 1175Hz.

The two following OAMP cells are set up as inverted comparators in order to generate the

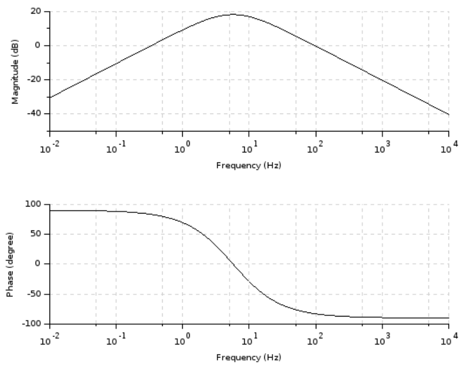

Figure 6. Second filter frequency response.

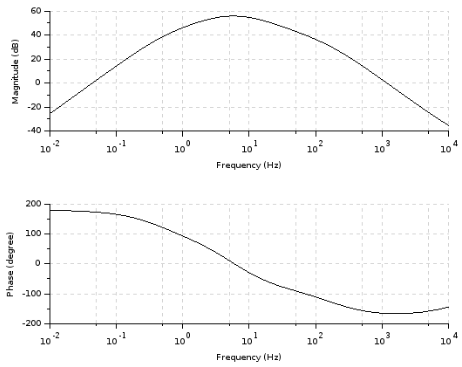

Figure 7. Global filter frequency response.

two output pulse signals. Each posses its own reference from a voltage divider: R3/R12 for P2 output and R11/R10 for the P1 one. Without modification those references are set to $\frac{20}{102}V_{in}$ for P1 (around 0.196 x V_{in}) and $\frac{1}{2}V_{in}$ for P2 ($V_{ref}1$ and $V_{ref}2$ in figure 3)
In addition, the P2 reference voltage could be adjust by user, connecting an external resistor or applying a given voltage between "thresh" pin (5) and ground reference.

B. Functioning principle

Firstly, as the OAMP is polarized positively, so only the positive variations of the input signal (from the photodiode) are amplified and filtered. Secondly, the steady state voltage at the first filter input is dependent of the supply voltage, hence as mentioned by Allen, the supply voltage has to be maintained as constant as possible in order to avoid any fluctuation on the photodiode voltage (not dust particle-dependent). Due to the absence of the capacitor C8 on the PCB (Printed Circuit Board), an external capacitor should be used (it is also possible to sold a capacitor in the C8 space).
Basically, when the input voltage varies, due to some particles, the filters amplify the positive variations of it by a total factor around 616 and the ultimate stage of the circuit compares the result with the two references. If this result signal is higher than 0.196 x V_{in}, then the pin P1 passes from high level (V_{in}- 0.6V) to low level (0.6V) which are the highest and lowest possibles voltages due to the built-in potential of the OAMP transistors. It is the same for pin P2 when the result voltage from the filters is higher than $0.5V_{in}$. Figure 8 resumes this basic theoretical functioning and figure 9 shows this for real small particles signal: a 3mV spike in TP16 input signal (blue curve) results in a 1.3V spike for output filter signal TP7 (red curve). P1 output level (purple curve) then changes from high to low since the TP7 signals overtake 0.98V which is the threshold voltage ($0.19V_{in}$). When the TP7 signal goes down below this same level the output P1 goes back to the high ideal state.

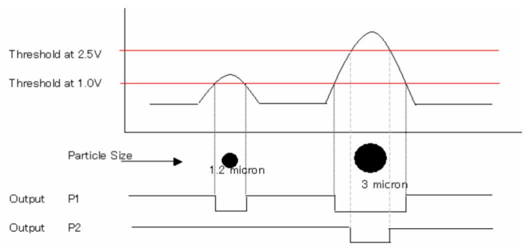

Figure 8. Detection principle (from Shinyei Technology Co, ltd).

The threshold voltages for the two output are settled by the manufacturer and P1 is supposed to give an information about particles size over $1\mu m$ and P2 about particles over $2.5\mu m$.
Note: As we can see in figure 10, the input signal is a little bit noisy with 1-2mV spikes at 200Hz. In our case, this perturbation comes from supply voltage which presents those 20mV/200Hz spikes despite of the presence of a 100μF capacitor near the sensor. However, as showed in figure 11, this kind of noise disappears after the filters.

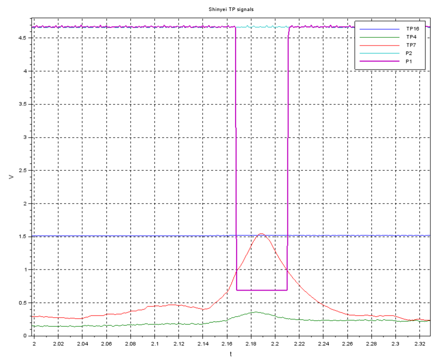

Figure 9. Internal signals for small particles.

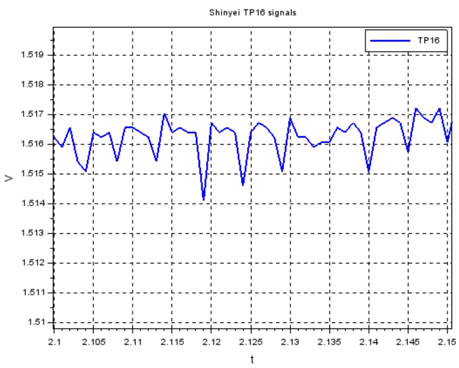

Figure 10. TP16 signal zoom showing a 1mV/200Hz noise.

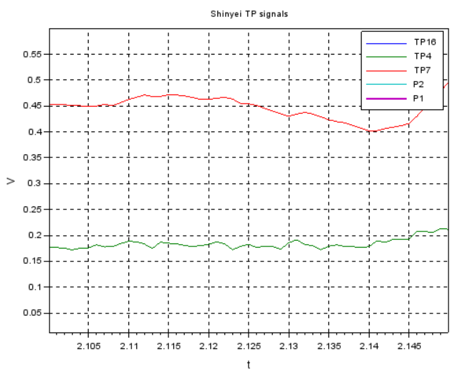

Figure 11. TP4 and TP7 signals showing the filters action.

C. The Low Pulse Occupancy time

As explained before, the duration of P1 (or P2) signal pulse is supposed to be in relation with the amount and size of dust particles that passes through the sensor (as showed in figure 8). More precisely, according to Shinyei, the sum of P1 (or P2) low level duration in a given time, for example 30s, is considered to be proportional to the quantity of dust particles (figure 12).

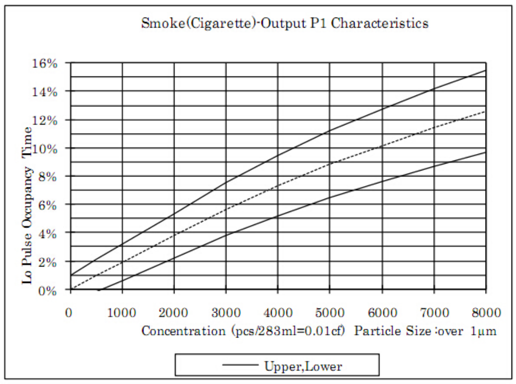

Figure 12. Relation between P1 LPO and particulate matter concentration (from Shinyei Technology Co, ltd).

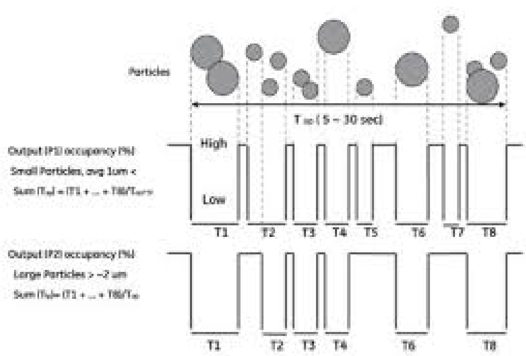

Figure 13. Particle size and LPO supposed relation for a Amphenol/Telaire SM- PWM-01A Dust Sensor, identical to the Shinyei (from [12]).

D. Limitations

1) LPO supply-dependency: Firstly, as mentioned above, the two threshold voltages are supply-dependent so the outputs pulse duration is also supply dependent. In case of supply voltage variations, especially at low frequency, the LPO of either P1 or P2 is susceptible to change without any relation to the particle size or quantity for which reason it is highly recommended to filter the power supply V_{in} as near the sensor as possible.

Secondly, since each output gives an information about the particle size *above* a given size (1 or 2.5 μm), the amount of particles with size *inferior* to 2.5 μm, called "PM2.5", is given by the subtraction of P2 LPO from P1 LPO.
Nevertheless, as figure 13 (from [12]) explains, this is only an approximation since the sensor is unable to differentiate a set of two or more particles of various sizes. Hence, a non-trivial algorithm need to be used to provide a good estimation of the particle concentration.

2) High-pass filter effects: As the two filters mentioned above are band-pass ones, the TP7 signal spikes have a maximum duration (more precisely this is a high-pass effect). Figure 14 shows the step response of the global filter: a large duration signal from the photodiode gives a limited duration signal at the filter output TP7. So, the result of the comparison with the threshold that produce P1 or P2 output is also a limited duration signal. Hence, the P1 or P2 LPO is not as proportional to the dust particle amount and size as expected. More precisely, the duration of P1 or P2 LPO is proportional to the photodiode signal amplitude until a given limit and for longer signals the LPO remains a this maximmun value. This could explain the nonlinear behavior of the Shinyei outputs, particularly when the dust particles concentration is elevated.
Figure 15 show this effect with real signals: due to the high level (250mV) and duration (400ms) spike in the input signal TP16 from the photodiode (blue curve), the first filter output signal TP4 (green curve) reach the saturation level (3.75V) during approximately 400ms but the TP7 output signal (red curve) shows a more limited duration (250ms). The duration of TP7 above 1V, the P1 output (purple curve), is only about 220ms in this case which is half of the input signal duration.

3) OAMP saturation: As showed in the same figure 15, due to the high gain of the first filter, when the input voltage reaches a "high" level (25mV + 1.51V), the output of the first filter reaches a saturation voltage of 3.74V which is below the OAMP saturation voltage (V_{in}-0.5V).

4) Air flow direction and perturbation: The airflow through the sensor is produced by a heater resistor placed inside the optic chamber near one of the sensor cover hole. This principle induce particle matter measure sensibility for three additional parameters: the heating time

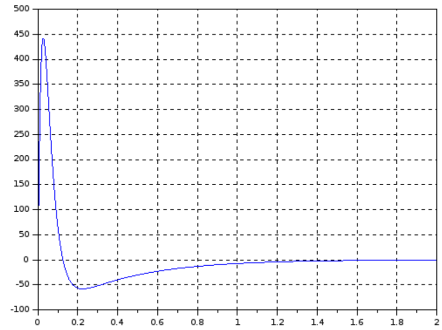

Figure 14. Step response of the global band-pass filter.

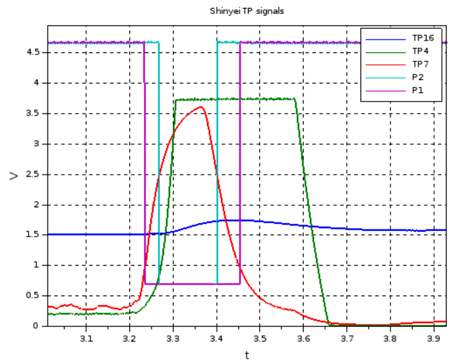

Figure 15. Sensor internal signals for large particles.

constant, the sensor orientation and the flow magnitude.
In the literature the *inlet* is considered to be the hole near the heater resistor, and thus, the *outlet* the one far the resistor. But, as we are going to show, this depends on the sensor orientation.
By measuring the air temperature gradient between the two holes it is possible to get informations about airflow velocity and direction (this principle is used in car motors airflow sensors for example). In this article we do not measure the airflow velocity but an estimation of it could be reach examining the temperature gradient, i.e. the difference between the two temperatures, taking into consideration the caloric transfer from the resistor to the air.
Since the airflow is created by an air temperature gradient produced by the resistor, it could be considered that the mounting orientation has an influence on the created airflow.

In particular, between horizontal mounting (sensor PCB horizontally oriented) and vertical mounting (sensor PCB vertically oriented), an analysis of the airflow temperature through the apertures shows significantly different behaviors as represented in figures 18, 17, 20 and 19. Those figures represent the airflow temperature just outside each aperture: T1 for aperture near the heater resistor and T2 for the other one (figure 16). The external perturbations from the moving air around the sensor were investigated putting it in a closed environment (a large plastic box) or in an open one (on the top of a table).
It is important specifying that the big hole at the center of the sensor plastic cover must be sealed, by cover tape for example (see figure 16), in order to ensure an adequate sensor functioning.

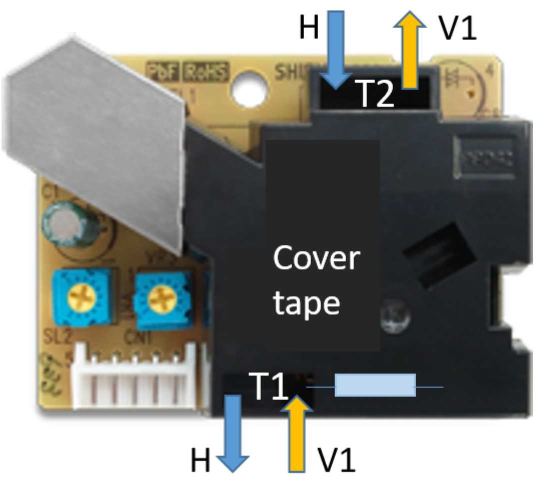

Figure 16. Sensor apertures and airflows (Notice in light blue the resistor position inside the cover).

In the horizontal mounting orientation, the T1 temperature is always higher than T2 when the heater resistor is on, which indicates a flow from T2 aperture to T1 (H blue arrows in the figure 16). This is pretty logical since the hot air at the bottom of the resistor ascends and leaves the sensor by the nearest aperture (where T1 is measured).

Two vertical mounting orientation are possibles: sensor connector up (V2) or down (V1). In the vertical mounting orientation called V1 (with the sensor connector to the bottom),

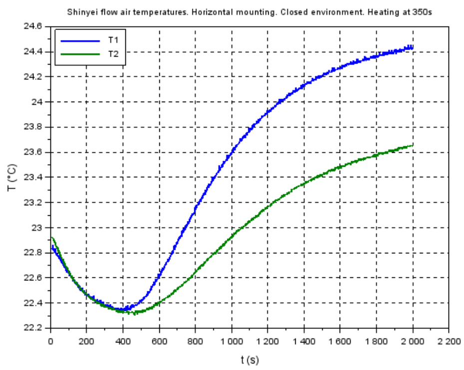

Figure 17. Air flow temperature for horizontal mounting and closed environment (Heating is on after t=350s)

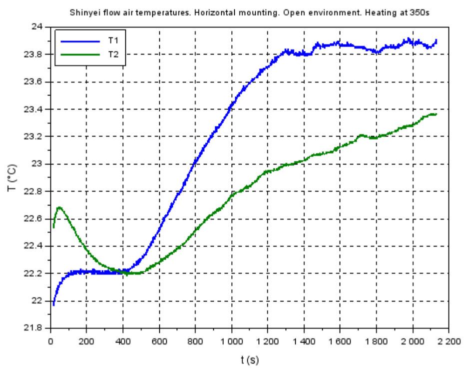

Figure 18. Air flow temperature for horizontal mounting and open environment (Heating is on after t=350s).

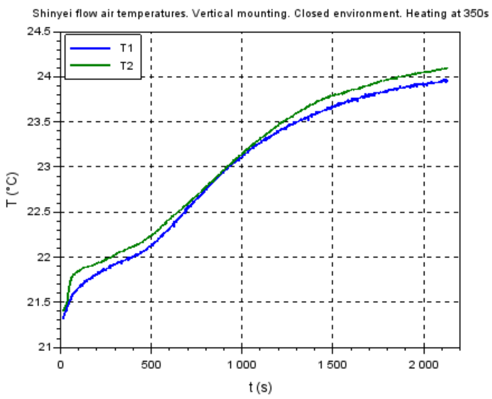

Figure 19. Air flow temperature for vertical mounting and closed environment (Heating is on after t=350s).

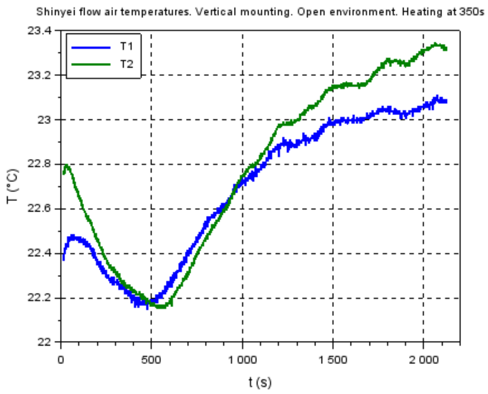

Figure 20. Air flow temperature for vertical mounting and open environment (Heating is on after t=350s).

the T1 temperature is always a little bit lower than T2 when the heater resistor is on, which indicates a flow from T1 aperture to T2 (V1 yellow arrows in the figure 16). This is the recommended position for this sensor: the hot air at the bottom of the resistor ascends across the optical chamber and leaves the sensor by the furthest aperture (where T2 is measured), this allows the admission of fresher air from outside by the bottom aperture where T1 is measured.
As showed figures 18 and 20, the airflow through the sensor - estimated by the temperature gradient - is more subject to perturbations when the sensor is placed in an open environment for either mounting orientations. This suggest a pretty high sensibility of the sensor for air movements outside it. In fact, if the airflow inside the sensor is not constant because of those perturbations, the PM concentration calculated from the outputs is subject to unexpected fluctuations since the measuring time used to calculate the LPO is linked to the air volume that passes through the sensor.
Finally, as showed in those figures, the high time constant of the airflow excludes any accurate measures before approximately 1500-2000s, hence 25-33 min. This is the necessary time to reach a thermal equilibrium for the system (heater resistor and plastic sensor enclosure).

E. Signal noise sources considerations

Due to it principle, the two sensor outputs are not affected by any background perturbation like electronic noise: the input signal noise from the photodiode is well filtered by the 2nd order global filter and the outputs are, in fact, numeric signals (a kind of pulse width modulation, PWM, but with variable frequency). However, most of articles show noisy measures from this sensor ([5], [6] among others).
One of the possible source of perturbation comes naturally from the sensor (through LPO variations, see III-D1) but the output post-treatment could also leads to some unexpected perturbations. In fact, analyzing the algorithms used by many authors, it could be demonstrated that those algorithms are somehow noise generators (in the sens of input-independent variations).
The literature present two algorithm variations for this sensors: measuring the LPO directly in the main C code or using a built-in function like `pulseIn()` for Arduino-like microcontrolers (AVR familly) used in the AirBeam project for example (see https://github.com/HabitatMap/AirCastingAndroidClient/blob/master/arduino/aircasting/aircasting_shinyeiPPD42NS.ino).
Those two algorithms are subjects to some inaccurate LPO measurements in the case where algorithm measurement period expires during a sensor output low pulse. When this occurs, the current low pulse duration is lost.
This has naturally fewer impact in case of large measurement period like 30s or more. But, as many new mobile applications require shorter acquisition time (one or two seconds for example), this impact increases since the ratio between LPO time and measurement also increases. In the most commonly used codes this case is untreated but can be easily fixed.

IV. Discussion and Operating Guidelines

As mentioned by some authors [5], the low cost dust sensor Shinyei PDD24NS is suitable for some classical applications in particular for measuring indoor PM2.5 concentration during large periods (in order to minimize the impact of airflow perturbations and LPO measurement). However, as demonstrated in this article, due to inherent characteristics of it, some other applications require a carefully implementation or should be avoided.
Hence, the sensor characteristics lead to the following implementation recommendations:

A. Supply voltage

The sensor supply voltage should be properly filtered in order to avoid any electronic noise or voltage variation coming from the others parts of the circuit (microcontrolers, fans, etc.) and susceptible to affects directly the output stage of the sensor (particularly the threshold LPO generator). So, a couple of high ($50\mu F \leq C \leq 200\mu F$) and low ($10nF \leq C \leq 100nF$) capacitors values and a adequate regulation is recommended. The use of Low Drop-off Voltage regulator is highly suggested in particular if the supply comes from a rechargeable battery.

B. Assembly considerations:

It is important to set the sensor orientation from the beginning of the device development and to keep it during all the operating. Any sensor orientation change should call a recalibration.
Likewise, the air movements outside the sensors have to be controlled and the mounting configuration (enclosure, inlets and outlets, internal heat sources, etc.) have to be kept unchanged during the set-up and operating. Any configuration change could drive to airflow modifications through the sensor and thus unexpected results regarding to initial set-up and calibration.
For mobile use, due to the tiny internal airflow, it is highly recommended to use a external fan in order to provide a steady stream inside the sensor. In this case, in order to avoid any turbulences inside the sensors it is recommended to extract the air from the sensor and not to blow the air into the sensor.

C. Data treatment:

A startup time has to be managed in order to let the sensor reaching the temperature equilibrium of the optical chamber.
Efficient algorithms should be used to ensure an accurate measurement. In fact, event counting and low pulse duration measurement requires a adequate evaluation of the code efficiency and execution time (for example, an Arduino Uno with a 16MHz quartz executes an C digital read or write instruction in about $7.8\mu s$).
In particular, the use of communication functions (in order to send data to a computer or other media) inside the measurement loop has to be carefully evaluated in order to avoid pulse loss. Likewise, implementation in assembly code or the use of C code optimization tools should be examined.

D. Nonlinearity:

The maximum LPO length limitation due to the internal saturation and filter characteristics leads to a loss of information: the length of the original event (from one single or a group of particles) that have generated the output low pulse, especially when the particle concentration increases. It is impossible to exactly compensate this by a post treatment since the model behind this phenomenon is unknown and seems to be erratic. At best, it is possible to only consider long time exposure (more than 1h) and to approximate the output by a third order polynomial function as many authors do, like [13] (or an exponential function or a combination of linear and nonlinear functions depending on the particle concentration) but for sampling period below a couple of minutes this kind of approximation doesn't work (said, there are too many outliers in the output data).

V. Conclusion

The low-cost dust sensors like the Shinyei PPD42NS (Syhitech DSM501A and Samyoung DSM501 in particular) allow a wide scale development for air quality measurement and monitoring projects due to their low-cost. However, for accurate data recollection, users have to pay attention to the mechanical and electronic implementation as well as to the software processing used. For moving applications in a real context (i.e. non-laboratory), this kind of sensors, without any modification (fan, original photodiode signal treatment), seems not adequate due to its inherent limitations.

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