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CREATIVE NANODEVICES

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A novel sensor solution for e-cigarettes

Enables smaller and less expensive MEMS sensors to now be used without false triggers

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Overview

Nanusens has filed a patent on how to avoid the false triggers that occur when MEMS sensors are used to replace the usual ECM sensors that detect when the user has inhaled on an e-cigarette and activate the heating element. The move to smaller and less expensive MEMS solutions has encountered a problem of unacceptable levels of false triggers that restricts take up. Until now, the cause of these false triggers has been elusive. Nanusens has discovered that the smaller air passageways of MEMS-based designs clog with oils that result in potentially dangerous false triggers. Nanusens' patented solution uses averaging algorithms on the data from an absolute pressure MEMS sensor in the e-cig and accurately identifies when the user inhales and thus prevents these false triggers.

Table of Contents

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1. The problem

Electronic cigarettes, or e-cigs for short, use a sensor to detect the air intake from the user in order to trigger the heating of a filament that will mimic a conventional cigarette. Although different types of sensors have been used, including a microphone to detect sound, it is accepted that the best current solution is to use a pressure sensor.

This is because a pressure sensor offers a reliable way to detect the user air in-take: other solutions may sometimes lead to a false trigger. False triggers are a big problem, not only because the battery is discharged without the e-cig being actually used, but they are also a safety concern. This is because, if the filament is heated in the wrong time, the e-cig may be inside one of the user's pocket or being held with their hands in such a way that the user could be hurt due to the high temperature of the filament that might even start a fire. Furthermore, generating smoke with the e-cig in places where smoking is banned could also be a concern.

So, it is really vital that e-cigs avoid false triggers. But, at the same time, however, we don't want to miss triggers either as the user would inhale but the e-cig not respond, which is a poor user experience and could be viewed as a manufacturer fault. Thus, it is really important to have an accurate trigger sensor in a e-cig.

The most widely used type of pressure sensor is an electret capacitor. This is an electret microphone, which usually has additional electronics integrated into the same package so that it delivers the trigger signal directly. This electret microphone for e-cig behaves as a differential pressure sensor. This means that it has two input ports with, typically, one located below the package and another one above. Inside the e-cig, the casing is made so that the above port is well connected with the cigarette holder or outside of the e-cig so that, when the user inhales, this port can quickly sense the pressure difference. The e-cig housing, however, makes it difficult for the air outside to get to the back port. This is deliberate so that, when there is a change of pressure outside, there is a delay until the back port of the differential pressure sensor can measure it. The result is that when the user inhales, the air pressure on the port above lowers but there is no immediate change in the back port. The e-cig pressure sensor is then programmed to trigger the output signal when the pressure difference between the top and bottom ports is approximately above 300 Pa.

The electret (or ECM – Electret Condenser Microphone) has many drawbacks. The main ones are the difficulty of reducing the production cost as costly soldering is required (which usually done manually and is prone to errors resulting in lower yields and thus higher cost for the e-cig), and large size. This is why there is a strong interest in moving from ECMs to MEMS ICs in SMD (Surface Mount Device) packages. Hence, there are several offerings from different manufacturers of differential pressure sensors for e-cigs on the market with the same functionality as e-cig ECMs, i.e., the output triggering the heating of the e-cig filament, and in an SMD package giving lower cost, smaller size and allowing automated SMT (Surface Mount Technology) soldering to improve yields.

However, they suffer from larger ratio of false triggers to the level where users and manufacturers are unhappy and therefore the uptake is poor. We have discovered that a key reason why these false triggers happen is the clogging of the path for the outer air to the back port of the differential sensor due to the oil generated inside the e-cig in addition to other particles from the smoke. This clogging can happen with ECM-based designs, but it is much more likely to happen with the new MEMS-based designs as these smaller devices have smaller pathways for the air that are thus easier to clog. And, when that happens, the pressure sensor no longer behaves as a differential pressure sensor but as an absolute one. In which case, if the ambient pressure changes more than 300 Pa, the sensor will trigger the output signal and the e-cig will heat the filament, i.e., a false trigger. For example, ambient pressure changes at about 10 Pa per meter so if you take a lift and move up 12 or more floors, you will false trigger the e-cig.

To the user, this false trigger seems to be a random event that disappears afterwards with the e-cig returning to normal functionality, which is why identifying its cause has been difficult as no fault could be found in the e-cig after the false trigger. Our theory of oil blockage ties in with the fact that the oil generated inside the e-cig has a relatively low viscosity. This means that, after clogging the air path to the back port, it will quickly evaporate or move away and thus the blockage that causes the false trigger has gone leaving no trace and a normally working e-cig. Although obviously, it can happen again and again for the same reason.

One may think that this can be easily solved by enlarging the air path from the outside to the back port of the pressure sensor. However, while this could prevent the path from clogging, it would significantly shorten the time delay for the back port to sense the changes outside the e-cig. As a result, the air in-take by the user would produce the same pressure on both the top and bottom ports of the differential pressure sensor and it would never trigger.

Another solution would be to increase the size of the package, allowing for an air path that delays the pressure change but does not clog so easily. However, this would eliminate the size and cost advantage of the MEMS pressure sensor IC.

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2. Nanusens solution

Nanusens has found a very simple solution to the problem. Instead of using a differential MEMS pressure sensor, we use an absolute MEMS pressure sensor and we average over time the readings so that we can emulate a differential pressure sensor.

This averaging over time of the pressure can be implemented in many ways. If we have the pressure in digital form, then we can implement a moving average. We could also use a fixed average that is recalculated for any given period of time such as one or two seconds.

If we don't have the pressure sensor in digital form, then we can add a high pass filter to filter out the DC value. In this case, the cut-off frequency of the filter would be equivalent to the averaging or recalculation time of the digital filter. In other words, the analog value of current or voltage representing the pressure over time would have to go through a high pass filter before being applied to a comparator that will trigger or not trigger the output signal to heat the filament.

These are just examples of implementing this but the concept is to calculate the average over time of the air pressure outside the e-cig and compare it with the instantaneous pressure that the sensor is measuring. Thus, when the difference is above the pre-set threshold, which usually is 300 Pa, the trigger signal is activated.

This approach means that the pressure sensor does not need to have two ports and we don't need to have the delay path for the air to the back port of the pressure sensor into the e-cig, which also simplifies the e-cig design.

In fact, this invention can be applied to any kind of pressure sensor. While Nanusens will use an absolute pressure sensor built with its *MEMS-in-CMOS™* technology, that further reduces size and cost, the concept can be applied to any kind of sensor, independent of the MEMS technology being used. And it can be applied to differential pressures sensors as well. Nanusens is licensing the use of this patent.

3. Algorithm and implementation details

In figure 1, the sensor data running average is shown (green line) and changes with time. As new samples are obtained, they are compared with the current average value and, if the absolute difference between the new sample and running average is less than a set value called AVE_THRESHOLD in the graph diagram, then the new sample is used to update the running average. If the absolute difference between the new sample and running average is greater than AVE_THRESHOLD, then the running average is not updated. A further threshold value can be implemented that is called TRIGGER_THRESHOLD in the graph diagram. If the difference between the new sample and the running average is greater than TRIGGER_THRESHOLD, then a trigger event occurs. The trigger event could optionally occur when the difference between the new sample and the current average value is greater than TRIGGER_THRESHOLD in either a positive or negative difference or both.

With this scheme, we stop averaging when the user inhales because, otherwise, we would move the average towards the pressure when the user inhales and we want to avoid that. In fact, the average is meant to keep track of the ambient pressure and not the lowered pressure that happens when the user inhales. This way, even if the ambient pressure changes substantially, the average will keep track of it and the device can still clearly identify a user's in-take that causes a difference of around 300 Pa to give a proper trigger.

This scheme requires a realistic starting average value before comparison operations start. This can be achieved by initiating the average with a known realistic value or by averaging the first N samples and using this as the initial running average prior to starting the comparison.

The multiple threshold levels described, AVE_THRESHOLD and TRIGGER_THRESHOLD, provide the opportunity to implement hysteresis on trigger events; the trigger asserts (signals the heater to activate) on crossing outside the TRIGGER_THRESHOLD and subsequently the trigger deasserts (removes the signal) on crossing back inside AVE_THRESHOLD.

In addition, optional debounce control can be added to the trigger event generation whereby new samples must cross the threshold settings for a number of consecutive samples or time or some other defined sequence before being considered a valid threshold event.

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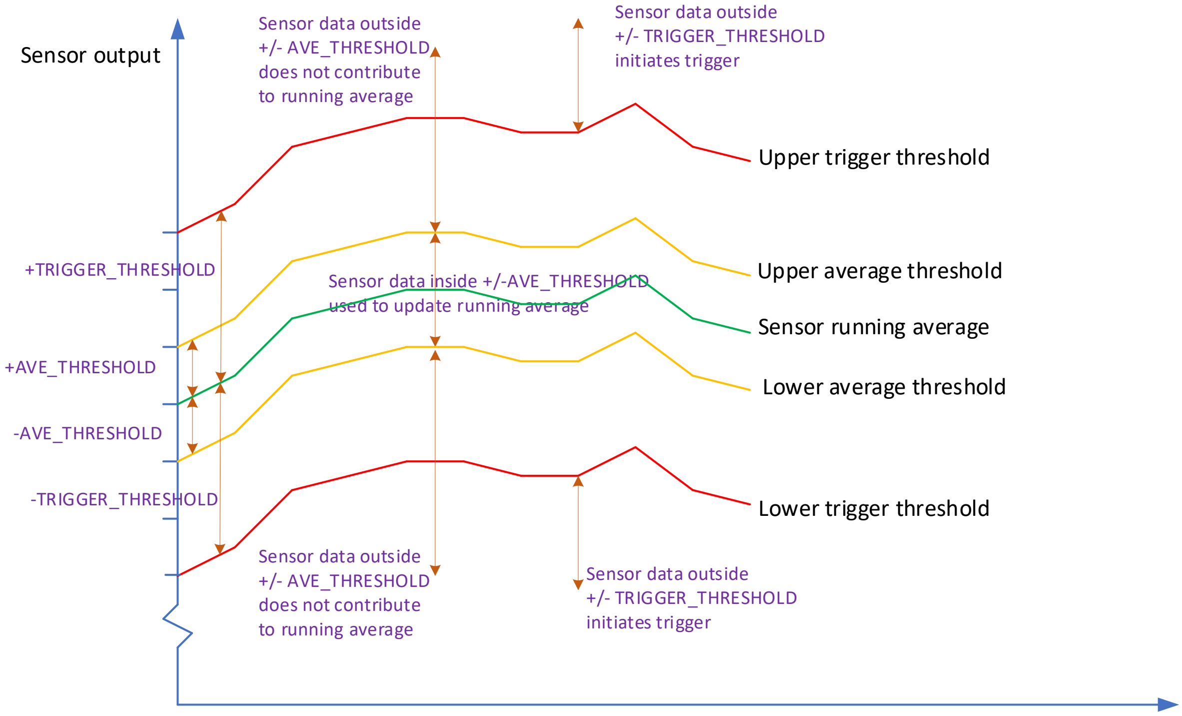

Figure 1. Signals explanation.

A simplified block diagram is shown below. The averaging scheme can be a block average, moving average or some other filter operation. The block average method implemented takes the average of N consecutive valid data points and computes the average. This process is repeated for the next block of N data points, and therefore the running average is updated with a new value every N data points. Alternatively, a moving (or rolling) average method averages N consecutive data points then re-computes with every new sample by averaging the new sample and the preceding N-1 samples, and therefore the running average is updated with a new value with every data point.

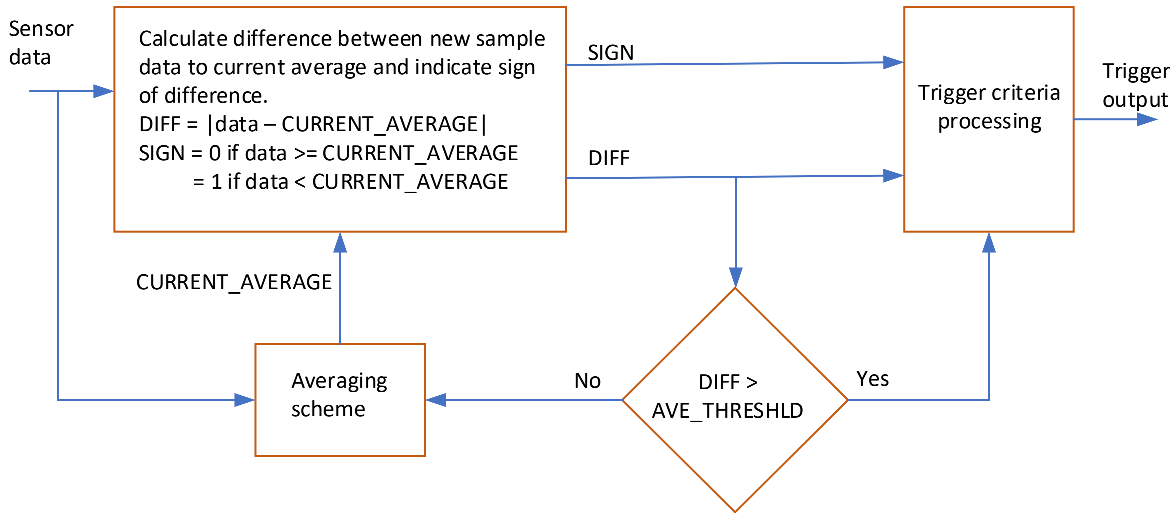

Figure 2. Sensor data algorithm to emulate a differential pressure sensor.

The threshold detection scheme relies on the ambient pressure changing at a rate below a certain level to avoid false triggers. Assuming a typical threshold setting of 300 Pa to cause a trigger in an e-cigarette application with a minimum sampling rate of 10 Hz, and a max block average sample size of 8 (causing a delay in the average update), an ambient pressure rate change of less than 750 Pa/s is required to avoid a false trigger. Ambient pressure reduces with height at approximately 10 Pa per metre, therefore the sensor would need to travel at an average vertical speed of 75m/s (270Km/hr) to cause a false trigger; fortunately the fastest vertical lift speed is approximately 20m/s. Other possible causes of fast ambient pressure changes are moving between the inside and outside of a building but such pressure differences are expected to be less than 100 Pa.

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The following figure shows the full e-cigarette system. Pressure sensor can be any type of digital pressure sensor, such as absolute or differential, or any other type.

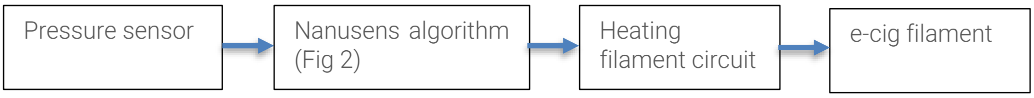

Figure 3. e-cig system

In addition to the blocks above, the e-cig will have also a battery with its power management unit that is typically rechargable from a USB port and an oil reservoir that is heated up through the filament generating the smoke. There is also the casing and, optionally, a button or some other additional fancy functionality such as LEDs to indicate charging, battery status and smoking. Some models also have a MCU to better control all the functionality.

The Nanusens algorithm to emulate a differential pressure sensor from an absolute pressure sensor can be applied inside the MCU if the e-cig has one or somewhere else. However, the preferred embodiment would be inside the same pressure sensor IC so that it can easily replace existing differential pressure sensors in e-cigs -- either ECM (electret module) or MEMS pressure sensor. Furthermore, it is also possible to integrate additional functionality into the e-cig pressure sensor beyond this. For instance, the heating filament circuit, the power management unit and/or the MCU. The more integration we get into the IC, the smaller size we will achieve results in a smaller e-cig and/or more space for the battery and oil, giving the e-cig longer times between battery recharges.

4. Further improvements to account for membrane changes

Another potential problem is that the oil (in addition to smoke and other particles, but mainly the oil) inside the e-cig can end up being deposited on the membrane and this can change the mechanical properties of the membrane. Although the membrane benefits from some protection of the IC package, there is a pathway for the oil that, with time, will end up reaching it. This change can be more or less permanent, although usually, the oil, being volatile and having low viscosity, will end up disappearing from there after some time. But maybe it is a permanent change? In either case, our algorithm will solve this problem. Because this will not be a sudden change but a gradual one as the oil is deposited on the membrane slowly with time. So, for any change that adds offset to the pressure measured, since it will be smooth, the average pressure will adapt to it and hence our algorithm will eliminate this effect.

In case of changes in the stiffness, we can compensate by improving our algorithm a bit more. In this case, we could run a moving (or fixed or any kind of) average of the peak delta pressure values that cause a trigger of the filament. Thus, every time that our algorithm sets a trigger to the filament, it needs to measure the pressure difference between the minimum pressure taken from the time when the trigger event is set until the trigger is released and the average pressure, note the difference (average pressure minus minimum pressure) and average that value. Then we will have a factor that will be 300 Pa divided by the average of this difference. This factor will be used to adjust all the thresholds of our algorithm, multiplying them by this factor.

A potential problem of this algorithm is that if, by any reason, the user inhales very strongly for a long time, the trigger will be adjusted to that as the algorithm will behave as if the membrane had become softer and the coefficient will be more than one. A consequence of this is that, if the user later goes back to normal or softer inhalation, the trigger will never be activated, so the e-cig will not ignite the filament and the algorithm will never be readjusted again.

A variation of the above algorithm improvement to compensate for slow changes in the membrane stiffness is to limit the coefficient to be always one or less. The effect of this is that the algorithm will only have an effect when the stiffness of the membrane increases, which is what happens with oil being deposited on the membrane, thus reducing the pressure difference needed to trigger the filament. This way, in the case that the user starts inhaling more strongly, the algorithm will not adjust the threshold levels as the coefficient will be kept at one. But, if the user starts inhaling more softly, the threshold levels will be adjusted and if the user later goes back to normal or even strong inhalation levels, the coefficient will go back to one and the threshold levels will be adjusted again.

About Nanusens™ www.nanusens.com

Founded in 2014 by Dr. Josep Montanyà and Dr. Marc Llamas, Nanusens is headquartered in Paignton, Devon, England with Research and Development offices in Barcelona, Spain and Shenzen, China. It leverages the research and expertise developed by the founders' previous company, Baolab Microsystems. Nanusens is VC funded by Inveready (www.inveready.com/venture-capital/), Caixa Capital Risc (www.caixacapitalrisc.es/en/) and Dieco Capital (www.dieco-capital.com), and several, ultra-high net worth investors. Nanusens has won the *Disruptive*

Innovation of the Year and *Emerging Technology Company of the Year* at the 2019 TechWorks Awards and *Best Campaign of the Year* at the 2019 Elektra Awards.

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