Barometric pressure sensors for consumer electronics

1 Introduction

The last few years have seen a remarkable increase in the number of use cases involving barometric pressure sensors in consumer electronics devices such as smartphones, tablets, wearable devices, and various home appliances. Barometric pressure sensors have been used for ambient air pressure measurement for several decades, however, recent developments and improvements in both these sensors and the devices in which they are installed have paved the way to superior performance and lower costs. The barometric pressure sensor has found its place across a wide range of products, no longer limited to traditional "weather stations". Today's barometric pressure sensors are so incredibly accurate that they can determine altitude to within just a few centimeters. This, coupled with low-cost manufacture, has made these sensors the mainstays for motion tracking, enabling what had previously been solely the realm of science fiction.
This paper will describe the two primary types of technologies used for pressure sensors, capacitive and piezoresistive, and subsequently, focus on several applications and key requirements.

2 The technology

On the surface, it is quite simple: a barometric pressure sensor detects atmospheric pressure. This output has traditionally been utilized in weather forecasting, in aircraft altitude meters, and so on. Declining atmospheric pressure indicates worsening weather conditions and vice versa. When a plane climbs to a higher altitude, atmospheric pressure decreases and conversely increases when the plane descends. Understanding this concept is essential to understanding the use cases we describe.

Air pressure measurement can be absolute, differential, or relative:

- Absolute pressure is measured relative to a vacuum
- Differential pressure is the difference in pressure between two different sources or locations
- Relative pressure is differential pressure measured in relation to the ambient air pressure

For practical use cases, differential or relative pressure is regularly used to derive the altitude or change in the vertical position of the sensor. By comparing measured air pressure to known ambient pressure at sea level, we can calculate altitude.

While there are many types of pressure sensors, the four main technologies are as follows:

- Piezoresistive: detects a change in electrical resistance of one or more resistors when pressure is applied
- Piezoelectric: measures a charge which is proportional to the pressure applied on the surface of a piezoelectric material
- Capacitive: detects changes in capacitance caused by the movement of a diaphragm
- Optical: detects changes in pressure due to their effect on light in an optical fiber

Piezoresistive and capacitive sensors are suitable for general purpose pressure measurement, such as industrial, medical and IoT applications. Piezoelectric sensors are suitable for high temperature applications such as aerospace, while optical sensors are good for harsh environments such as aerospace, oil, and gas.

For barometric pressure sensing, the two most popular options come in the form of piezoresistive and capacitive sensors. Bosch Sensortec offers both technologies. Piezoresistive pressure sensors from Bosch have always been best-in-class, with Bosch dominating this market segment. Nevertheless, the recent launch of the BMP580 and BMP581 capacitive sensors has raised the bar for performance to an entirely new level, whilst leveraging Bosch's decades of MEMS experience in the process.

For example, if we compare the BMP580 (capacitive) with the previous generation BMP390 (piezoresistive), the improvements are more than striking:

	Current[1]	Noise[2]	TCO[3]
Previous gen.	17.1 µA	1.12 Pa_{rms}	1.2 Pa/K
	-85%	**-80%**	**-33%**
BMP580	**2.5 µA**	**0.21 Pa_{rms}**	**0.8 Pa/K**

[1]vs. BMP390 at same noise level (0.72 Pa_{rms}) and 1 Hz data rate; [2]vs. BMP390 at same current level (190 µA) and 30 Hz data rate; [3]vs. BMP390 spec.

Figure 1
Improvements of BMP580

The BMP580 uses leading MEMS core technology housed in a completely new package. It is ideal for applications requiring high precision yet very low power consumption, notably battery-driven portable devices such as smartphones, smartwatches, and hearables.

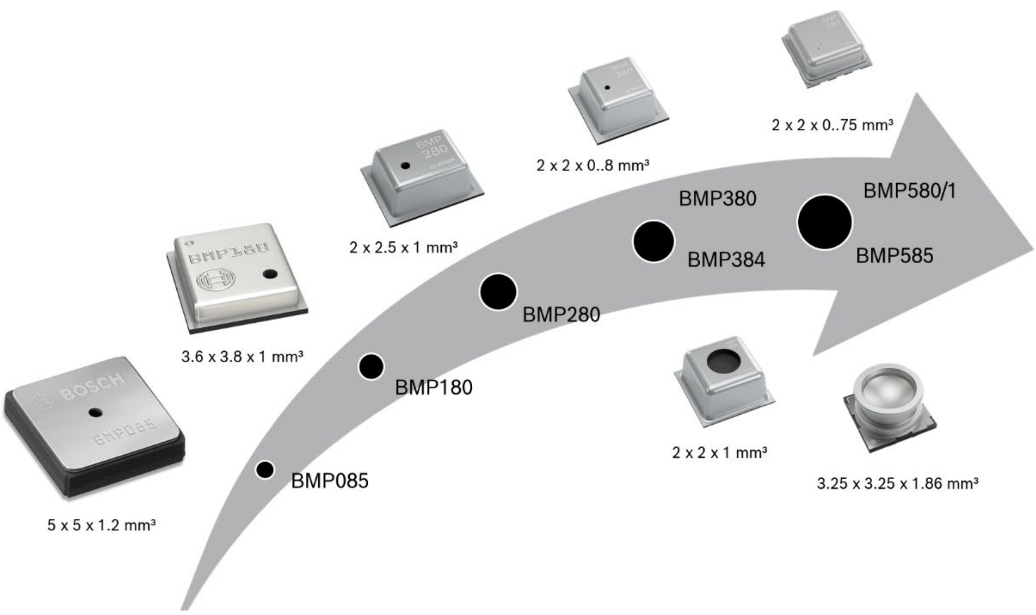


Figure 2
Continuous improvement in performance and size reduction over five generations

3 Use cases

Environmental sensors for barometric pressure, humidity, temperature, and air quality have become smaller, cheaper, and more accurate – whilst using increasingly less power. This has enabled them to gradually find a plethora of uses in consumer electronics.

Barometric pressure sensors are the most used environmental sensors in high-end smartphones. The wide range of applications that enhance people's health and well-being include:

- Indoor navigation
- Indoor localization
- Fitness tracking
- Fall detection
- Water level detection
- Blood pressure measurement
- Drone navigation

Let's take a closer look at these applications one by one.

3.1 Indoor navigation

It can often be quite tricky to find your way around large buildings such as malls, airports, and skyscrapers.

GNSS systems, such as GPS (Global Positioning System), have a fundamental weakness: the GPS signals from satellites have problems penetrating the thick walls of buildings and can be frequently blocked by high buildings (in so-called urban canyons), trees, and other obstructions.

In these so-called GPS dead zones, the GPS signal is blocked, making navigation nearly impossible – it becomes difficult for a device in such an environment to obtain a GPS signal or to achieve reasonable vertical accuracy. Prevented from receiving altitude information, the GPS device is subsequently unable to detect its vertical position on different floors.

However, if your smartphone has a built-in barometric pressure sensor, it can accurately detect its altitude by taking air pressure measurements. This means it can determine on which floor you are located, enabling you to easily navigate through large shopping malls, parking lots, airports, subway stations, and so on.

Step counting and fitness tracking functions benefit greatly from knowing whether you are walking up or down stairs, your current floor, and whether you have climbed or descended.

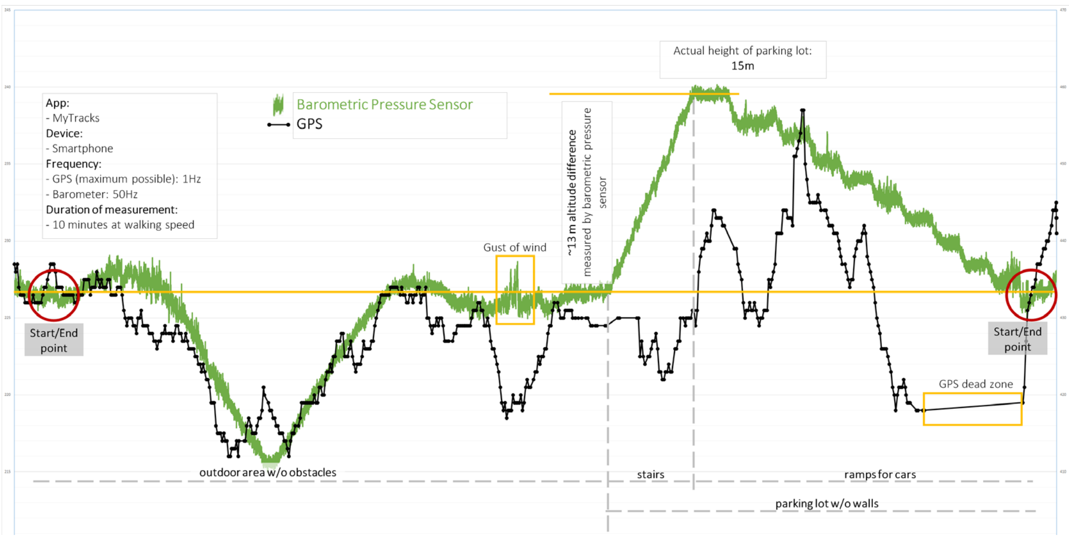


Figure 3
Barometric pressure sensor vs. GPS altitude tracking

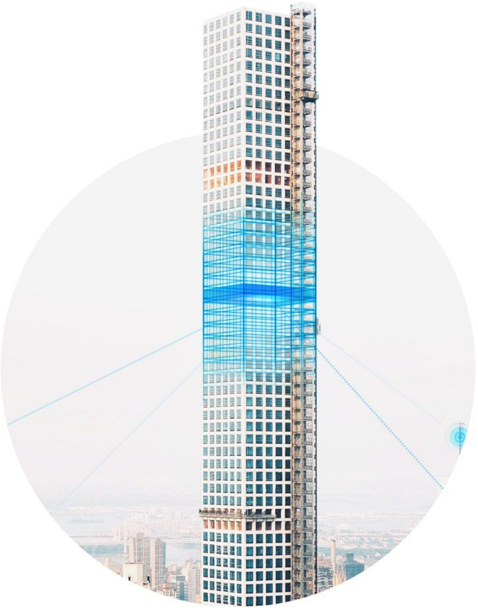
Figure 3 shows how data from a barometric pressure sensor compares to GPS data on a timeline. Initially, the GPS device achieves relatively good accuracy compared to the barometer because the first few minutes are measured in an area with no trees, buildings, or other obstacles in the vicinity. However, when approaching a parking garage, the accuracy of altitude measurement starts to decrease. Once inside the parking garage, it is no longer possible to obtain a GPS data point every second, since the roof is blocking the signal. This four-storey parking garage has no walls, so sometimes it is possible to receive a signal, however, the altitude accuracy exhibits significant errors.

Using barometric pressure for altitude measurement must reflect the fact that air pressure is not static over time and fluctuates based on current atmospheric conditions and weather. Ambient pressure can change significantly in just a few hours and may be equivalent to ascending or descending more than 100 m. The key to solving this issue is to simultaneously measure weather-induced atmospheric pressure changes at multiple fixed locations, and then to use this information as a real-time reference for the actual pressure readings measured using the sensor in the smartphone.

In order to improve altitude measurement accuracy for an entire metropolitan area, highly accurate barometric sensor stations are installed at surveyed reference points at known heights. These are then used to measure and ultimately compensate for changing weather conditions, including the effects of local microclimates.

3.2 Indoor localization for emergency calls

The use of mobile phones for making emergency calls is increasing and so there exists an opportunity to automatically provide an accurate location of the caller to the responder. For example, in the United States, rule E911 from 2015 requires that the location of a 911 caller be transmitted to the responder.



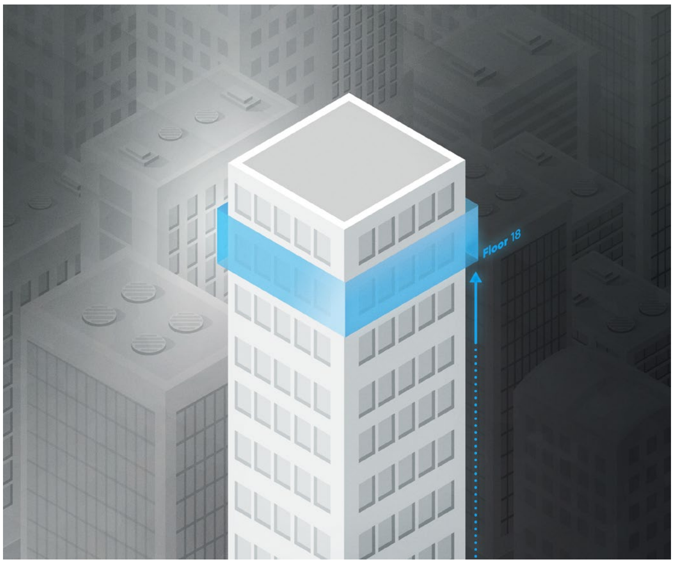


Figure 4
Rule E911 (Source : NextNav)

However, many 911 calls are made from inside buildings, where traditional localization technologies are ineffective or fail outright. To overcome this weak point, barometric pressure sensors can provide accurate altitude data that helps to pinpoint people when located inside buildings, where GPS signals are, as a rule, weak or unavailable. The addition of floor-level information about smartphone users thus enables first responders to get to the scene faster, which has the potential to save thousands of lives.

The Federal Communications Commission (FCC) has specified that the vertical accuracy required for 911 calls must be within 3 m for 80% of calls made to emergency dispatchers. This specified "floor level" vertical-location threshold must be achieved by April 2023 for the top 50 markets in the US.

Of course, many potential solutions to overcoming indoor localization problems have been considered, including Wi-Fi, RFID, and even Bluetooth Low Energy (BLE). However, none of these have been able to effectively achieve today's required vertical accuracy level. "Where there's a need, there's a way", and the US-based company NextNav has met this challenge head-on by developing a dedicated altitude measurement system that can provide FCC-required vertical accuracy across an entire metropolitan area, utilizing Bosch’s barometric pressure sensors.

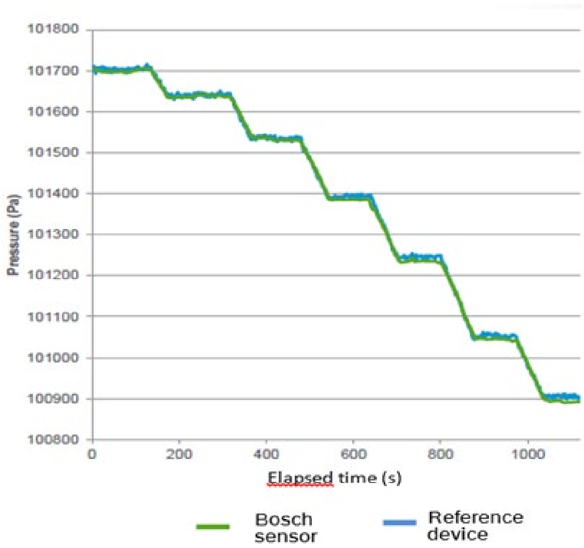


Figure 5
Bosch sensors are as accurate as reference devices for air pressure tracking (source : NextNav)

3.3 Fitness tracking

Pressure sensors can be used to measure relative vertical height changes of different parts of the body. By utilizing multiple sensors, for example in earbuds and a wrist-worn fitness tracker, the obtained movement data can be used for detailed analysis of the wearer's movement over time (see Figure 6).

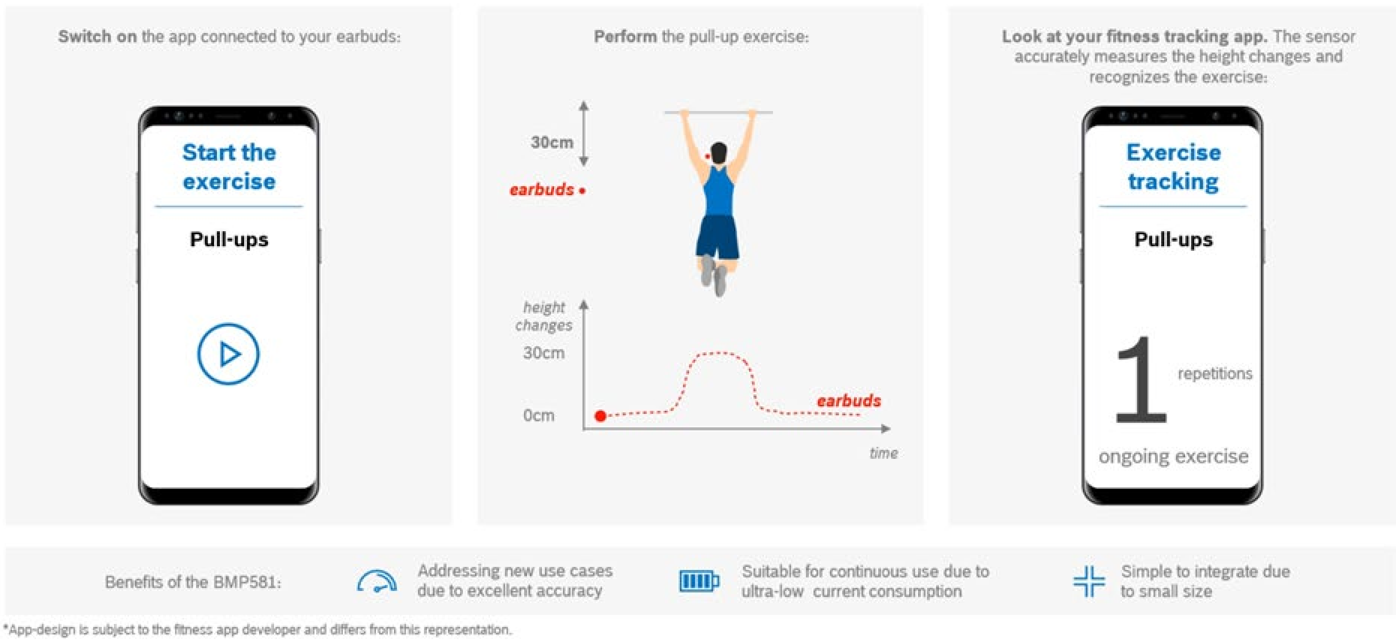


Figure 6
Measuring smallest height changes during pull-ups with the barometric pressure sensor BMP581

During exercises such as pull-ups or push-ups, even tiny changes in height must be measured with great accuracy. For this to be possible, the sensors must have high relative accuracy and low noise, coupled with very low power consumption and high environmental robustness. Furthermore, the sensor must not exhibit any drifts in the readings over the typical duration of the exercise program, which is usually around 10 min.

Accuracy is the key factor, and a resolution of less than 4 cm is needed for motion detection. Today's capacitive pressure sensors achieve precision levels that enable highly accurate tracking of walking up and down stairs (see Figure 7).

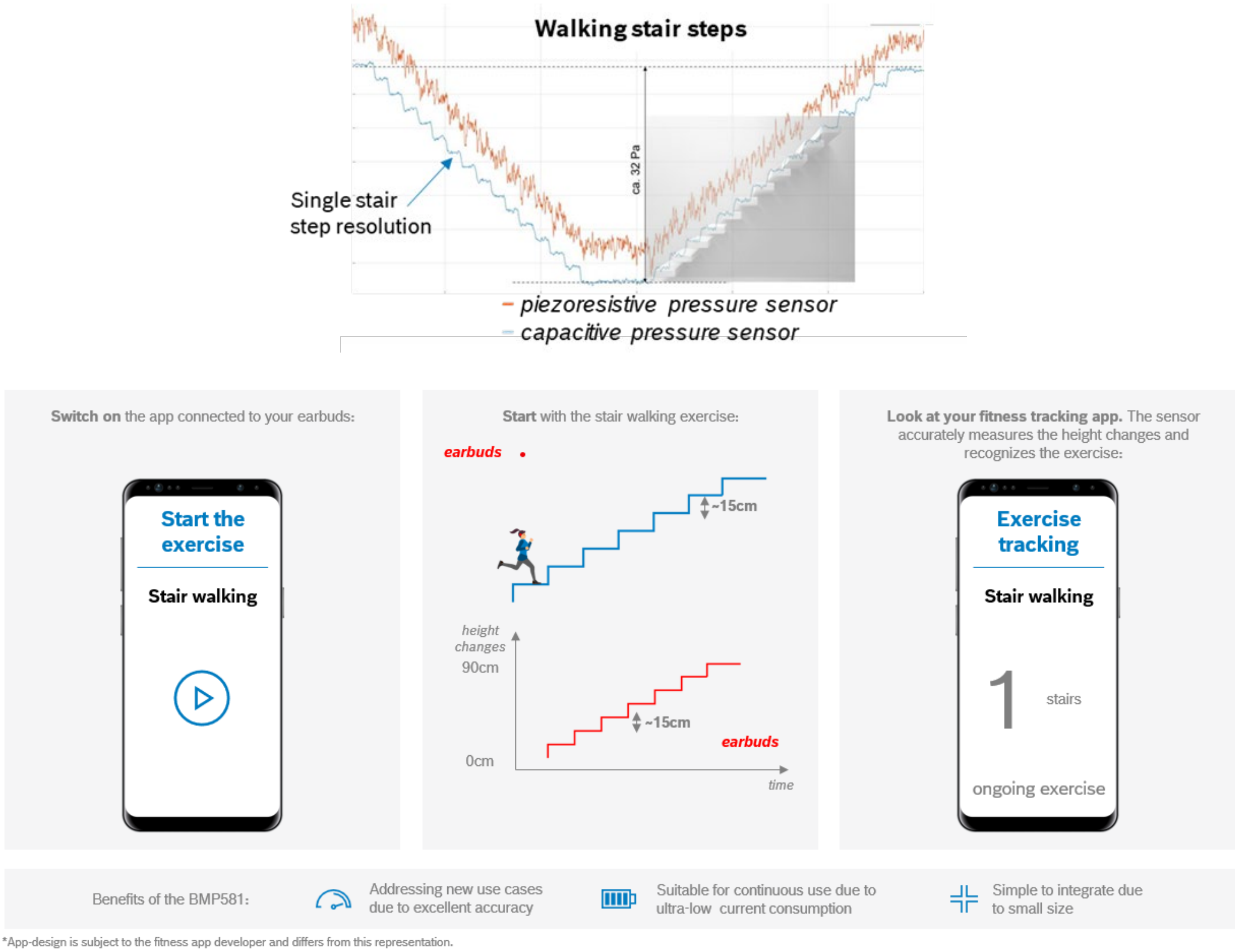


Figure 7
Tracking stair climbing

Compared to previous generations, Bosch's BMP581 capacitive pressure sensor has significantly reduced its noise and power consumption and now provides highly accurate and dynamic measurements, enabling pull-ups, sit-ups, or single stair steps to be easily measured.

To put this into context: the atmospheric difference for a typical step height of 17.5 cm is 2 Pa, which corresponds to a mass difference of 7.6 µg of air for the sensor, equivalent to one thousandth of the mass of a mosquito! The sensor experiences a capacitance change of 12.6aF, a charge difference of 60 electrons. Its membrane gets deflected by approximately 6 x 10-12 m, which would be equivalent to just 120 µm, or double the diameter of a human hair if the membrane were to be scaled up to the size of a soccer field.

3.4 Blood pressure measurement

In the medical field, barometric pressure sensors are used for non-invasive blood pressure measurement, using an in-ear sensor installed inside a hearing aid or other wearable device.

A highly sensitive pressure sensor, hidden in the ear canal, measures the blood pressure of the ear canal capillaries. This enables non-stop recording day and night, which is often far more useful for precise diagnosis than taking just a few arbitrary measurements.

Why the ear? The heart supplies the head and brain directly, which means that the ear is always well supplied with blood. Interference from the chest or neck muscles is low, compared to other parts of the body, where movement can introduce measurement errors. In the ear canal, the blood vessels lie directly beneath the skin and are therefore easily accessible for miniaturized sensors.

In a prototype application, currently under development in Germany, a BMP580 pressure sensor is used to provide highly accurate measurements of comparable precision to those obtained using a conventional arterial catheter inserted inside a large artery. A small inflatable balloon is used to squeeze capillary vessels in the ear canal for a short period, which enables the pressure sensor to measure the absolute values of the blood pressure for calibration purposes.

3.5 Drones

Drones are becoming very popular, but they require some quite sophisticated electronics to make them easy to fly. Typically, a barometric pressure sensor (such as Bosch Sensortec's BMP581) is built into the drone to provide altitude information for improving flight stability, altitude control, take-off, and landing performance.

The barometric pressure sensor precisely measures altitude and in combination with readings from MEMS motion sensors in the drone it can be used for altitude control. The pressure sensor must reduce and eliminate external influences and inaccuracies as much as possible. Today, with additional sensors such as GPS and optical flow, distance sensors are used to improve the reliability of the system and reduce positional errors.

The requirements placed on pressure sensors in a drone are often extremely rigorous. Subject to the effects of adverse weather and temperature conditions, altitude accuracy must remain within a very tight tolerance band, and the sensor must exhibit low latency and negligible drift over time.

3.6 Fall detection

Dropping an electronic device, such as a smartphone or laptop, may not necessarily break it, but may cause substantial damage. If the fall is detected quickly, the device can react and prepare itself for impact before it hits the ground, for example by parking the hard disk head in a laptop or covering a camera lens on a smartphone.

Detecting falls of people is also important – the ability to recognize and report an emergency is fundamental for seniors to be able to feel safe and secure in their old age.

Fall detection can be achieved by using a pressure sensor, such as the BMP581, together with an IMU motion sensor. With Bosch sensor solution software, this system can evaluate the sensor data to determine whether it represents a fall, where action is required. By combining data from both a pressure sensor and a motion sensor, overall accuracy is increased, and the number of false positives and false negatives can be minimized.

3.7 Water level detection

Detecting the water level inside a washing machine drum is important for avoiding flooding and helping to reduce water consumption and can be performed using a barometric pressure sensor, as shown in Figure 8. The water depth is calculated as follows:

Without water: $P = P_0$
With water: $P = P_0 + P_w$
$P_w = \rho * g * h$
Therefore $H \approx h = (P - P_0) / (\rho * g)$

P = *Measured pressure [Pa]*
P_0 = *Reference pressure (atmospheric pressure) [Pa]*
P_w = *hydrostatic pressure [Pa}*
ρ = *Water density [kg/m³]*
g = *Acceleration due to gravity [m/s²]*
h = *Height of the liquid column [m]*

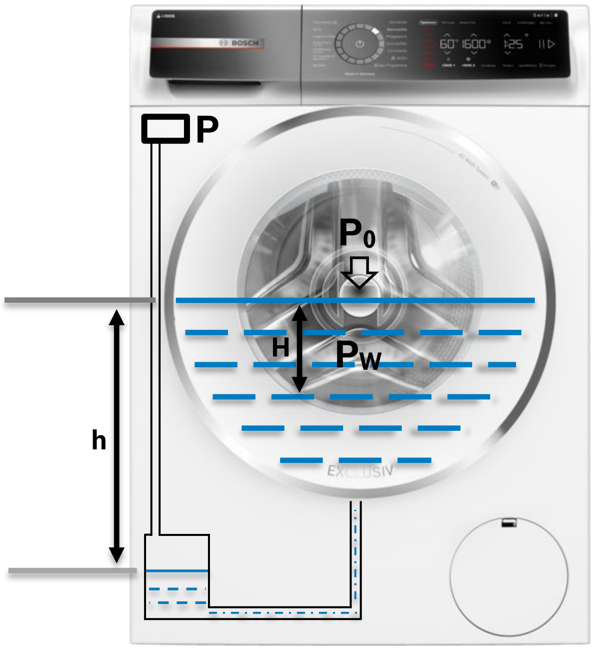


Figure 8
Pressure measurement to determine the water level

By using a MEMS pressure sensor, the washing machine benefits from the reliability of a measurement system that has no moving parts. The water level measurement system provides high accuracy and uniformity, in a very small size. Compared to previous solutions, its mechanical design and assembly are simple and material costs are reduced.

3.8 WIFI 6 GHz

Wi-Fi is the standard for over 20 years to wirelessly connect devices in the home, office and countless other places using the unlicensed 2.4 GHz or 5 GHz spectrums. The requirements for devices with Wi-Fi capabilities continue to increase, therefore the need for better connectivity and improved speeds grows. This will be possible with additional bandwidth. Therefore, Wi-Fi 6E/7 has been introduced by many countries to help meet the increased demand for reduced congestion, improved bandwidth, and faster speeds. Wi-Fi 6E/7 expands the capabilities of Wi-Fi 6, enabling devices to operate in the unlicensed 6GHz spectrum where it makes use of super-wide channels that support greater capacity, lower latency, and increased throughput.

FCC has authorized the use of 2 different types of unlicensed operations in the 6 GHz band, making 1200 MHz in the spectrum available for these types of operations.

- Indoor low-power operations – Authorized for use in the full spectrum.
- Standard-power access points – Authorized for usage with an Automated Frequency Coordination (AFC) System.

The AFC system provides information of the available frequencies to the stand-power access points.
This is to ensure that the unlicensed user of the spectrum does not interfere with the existing users of the 6 GHz band.
The access point must report the location and antenna height, so the AFC can calculate the availability of frequencies and channels of operations. Pressure sensors are now being considered as the potential solution for antenna height calculation.

To mitigate interference issues the frequencies and the point angle of the antenna systems are recorded and managed by the AFCs. Wi-Fi-6E/7 providers are required by FCC regulation FCC-20-51 (https://docs.fcc.gov/public/attachments/FCC-20-51A1.pdf) to report the height above ground of Wi-Fi APs operating at the higher SP power level and in the 6 GHz spectrum to the AFCs.

Key requirement is to be within an accuracy confidence level of 95%. Also, for access point installers and system operators, a solution that provides an automated method for recording the vertical location of the access points becomes critical to meeting the FCC requirement in a cost-effective manner. It is mandatory to provide an altitude measurement that is consistent with FCC requirements for the measurement format. Most devices provide a Height Above the earth's Ellipsoid (HAE) and therefore, altitude measurements from a device are not sufficient, especially in hilly areas. The FCC measurement format in determining the altitude measurements is height above ground, also known as Height Above Terrain (HAT).

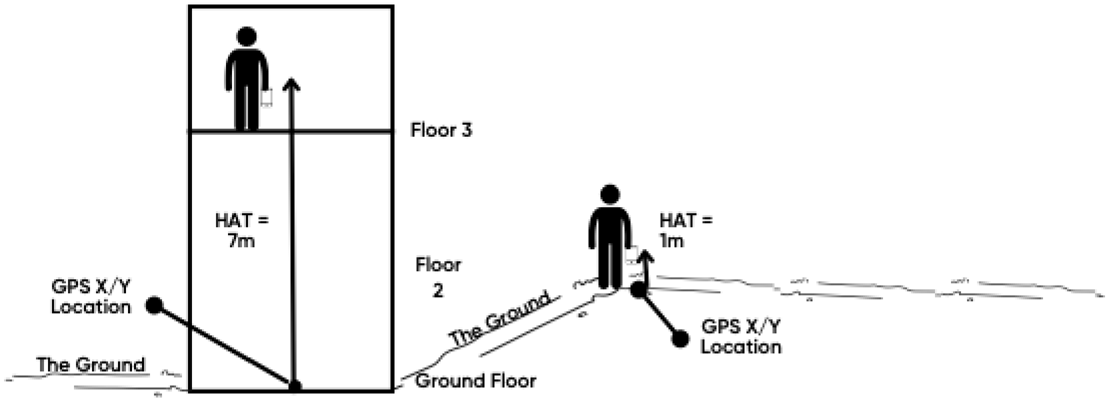


Figure 9
Altitude measurement (Source : NextNav)

You can visit https://nextnav.com/hae/ and https://nextnav.com/hat/ for more information on the topic or read the white paper on the topic here: Bosch-NN White Paper (bosch-sensortec.com).

3.9 More applications

Here, we have explored several interesting applications for barometric pressure sensors, however, there are many more that are possible. Let's take a brief look at four more use cases:

- Laptop fan failure detection: Currently, laptop manufacturers monitor the fan's status using a rotation speed sensor, but unfortunately this means that there is no way for the laptop to detect a cooling failure caused by the air channel being clogged with dust or debris. However, data from an air pressure sensor can indicate when cooling air is not flowing correctly – either due to a failed fan or a clogged airway.
- Clog detection in vacuum cleaners: The level of dust inside the dust bin is estimated by monitoring the flow of air through the dust bin with a barometric pressure sensor. The air pressure inside the dust bin when it is empty will be compared to the air pressure inside the full dust bin. It begins to drop when the air flow becomes to stagnate due to an increase in suction dust or clogging of the filter. Additionally, the vacuum cleaner motor can be adjusted depending on the floor material like carpet or hard floor.
- Precise user movement tracking in Augmented Reality (AR) and Virtual Reality (VR) applications: accurate measurement of height is essential across multiple devices such as glasses, hand controllers and fixed reference anchors (sub-cm-resolution with the lowest possible latency is required for a realistic presence experience). Environmental influences like open doors/windows and air conditioning can be recognized by Machine Learning (ML) techniques and handled accordingly. Stable temperature behavior is needed for mm-level accuracy.
- Smartphone weather stations: Deliver precise weather forecasts for temperature, relative humidity, and barometric pressure. Specifically, a barometric pressure sensor can indicate weather and altitude changes; this information significantly improves weather forecasts for every location.

4 Conclusion: Your daily companion

With their growing usage in smartphones, wearables and hearables, barometric pressure sensors will become everyone's daily companion.

Today's capacitive pressure sensors, such as the BMP581, provide incredible accuracy coupled with low power consumption in a tiny, robust package. This enables them to find use cases across many diverse applications in consumer electronics – and just wait, there will be more that haven't even been invented yet!