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Article

Floor level estimation using MEMS pressure sensors

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SUMMARY

Enhanced 911 systems aim to increase the efficiency of first responders by automatically locating the origin of a 911 call even if the caller is unable to provide it. However, in a high-rise building, the location of a cell phone call would appear the same to dispatchers regardless of elevation. If emergency services had more accurate location information, they could save countless more lives. In this study, we compared multiple methods for determining a caller's floor level inside a building, including GPS, WiFi, a magnetic sensor, and a micro-electromechanical system (MEMS) pressure sensor. GPS provided a reasonable estimate of vertical height, but accuracy was strongly dependent on the reception, which was often poor inside the building. WiFi signals and magnetic fields were not strong predictors of vertical height. WiFi was limited by short signal range, need for network access, and knowledge of router locations. Magnetic sensor readings required a pre-existing magnetic field contour map of the building in order to interpret the data. The MEMS pressure sensor was the most accurate predictor of elevation and does not rely on communication with other equipment. A detection accuracy of ±1 floor can be achieved using the MEMS pressure sensor after correcting the output using publicly available data and assuming an average floor height. The proposed technique provides a self-contained solution, using a sensor available in most smartphones, to determine the floor of a caller. Adding floor level data to emergency call locations would provide valuable information to first responders in densely populated urban areas.

INTRODUCTION

The 911 program in the United States has been crucial for public safety for several decades. 911 provides a direct and accessible way to reach emergency services when someone needs immediate help. The program has been continually keeping up with technological advances through systems such as Next Generation 911 and Enhanced 911 (E911) (1). In E911, the physical location of the call is automatically provided to the dispatcher, as opposed to the caller having to verbally provide their whereabouts. Several technologies are used to determine the location of the caller, including Global Positioning System (GPS), wireless networks (WiFi), and inertial navigation. Although these technologies provide adequate accuracy for the latitude and longitude of the caller, they have limitations when it comes to altitude (2). A typical scenario that highlights this issue would be when the emergency call originates from a multistory building or a high-rise. Dispatchers would be able to determine the location of the building on a map, but not the exact floor the call came from. This inability to detect the exact location of the caller can be a significant issue in major cities where 911 calls from skyscrapers are common.

GPS and pressure sensors are techniques typically used to locate a caller outdoors, whereas WiFi signal strength and magnetic field maps are used for indoor location assessment (3-5). GPS uses a technique called "triangulation" using satellites that are in orbit 11,000 miles above the earth (6). A cellphone with a GPS receiver can calculate the distance to a satellite using the time it takes for radio signals to travel between the two. Radio signals travel at the speed of light, which is a constant. By measuring the time, one can calculate the distance, since distance is equal to speed multiplied by time. Multiple satellites (at least three) are needed to pinpoint the location of the caller. Distance measured to a single satellite can be at multiple points on the earth's surface along a sphere. However, with two satellites, the sphere reduces to a line since the intersection of two spheres is a circle. Finally, using 3 satellites, the line can be reduced to 2 points, only one of which is on Earth's surface. This technique works well outdoors, but GPS signals can be weakened significantly by structures, such as concrete walls and floors (7). Recently, researchers developed the same triangulation technique using WiFi signals instead of GPS signals (4). Here, the source is a WiFi router instead of a satellite and three or more routers with fixed locations are used to triangulate the signal.

Magnetic field maps work differently from triangulation. Our planet is made up of different layers, including the inner and outer core, mantle, and crust. Earth has a magnetic field that is created by electric currents in the liquid outer core (8). Earth's magnetic field is similar to that of a bar magnet with the magnetic north that is close to the geographical south pole and magnetic south that is close to the north pole. The earth's magnetic field has been used for navigation for a long time and forms the basis of how a compass works (9). Most smartphones today have a magnetic sensor that can measure the local magnetic field. The earth's magnetic field can be distorted by ferrous objects in the environment, such as steel reinforced concrete structures of a building. The idea behind magnetic field mapping is that the distorted field will be unique. By making measurements in several locations inside a building, a magnetic field map can be constructed (10). The resolution of the map will depend on the density of measurement points. Then using a technique called "pattern matching," the current sensor readings can be compared with the recorded map to identify the location of a person.

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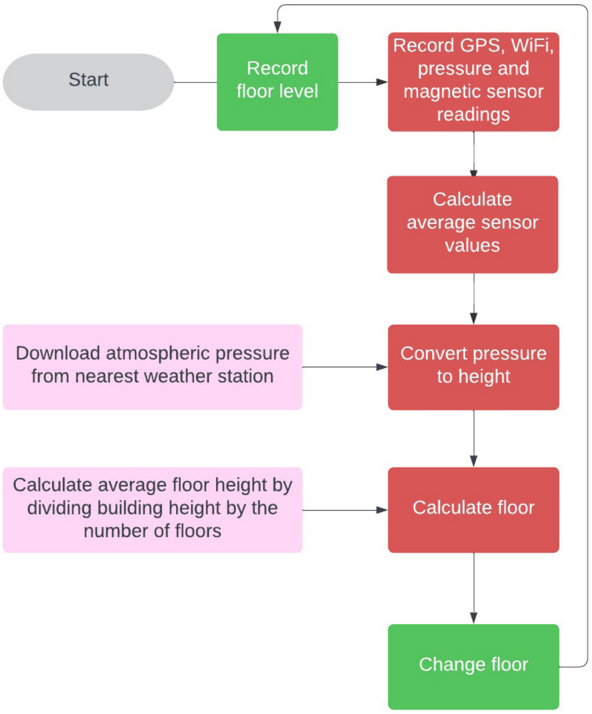

Figure 1: Experimental technique and data processing steps. The flowchart describes how the experiment was conducted starting with sensor readings taken at different floors, averaging and calculating the caller's floor, which are shown in red. Any external data sources that were used in the calculations are shown in pink.

This is similar to how a GPS locates a person on a map by comparing the latitude and longitude readings to a recorded map of a city.

An altimeter is a type of sensor that measures changes in altitude by measuring the ambient air pressure at a given elevation relative to a reference level (typically sea level) (11). Ambient air pressure is the force exerted by the weight of the air above an object. An altimeter works on the principle that pressure reduces with altitude. This means the higher up a person is, the less atmospheric pressure they experience. Pressure can be converted to vertical height or altitude using the barometric formula, which takes into account pressure sensor readings and local atmospheric pressure (12). For consumer applications, a sensor needs to be small enough to fit into a watch or a phone as well as energy-efficient for longer battery life. These small-scale sensors found in modern devices are known as micro-electromechanical systems (MEMS). MEMS is a technology that can be used to manufacture miniature sensors in the same way as computer processors or memory chips are made (13). These systems can be used to create mechanical structures that, in combination with electrical circuitry, create a complete sensing system (13). There are several successful examples of MEMS sensors in the market today, including accelerometers that can detect a car crash, microphones that can pick-up sounds including human speech, light sensors to adjust screen brightness, and many more (14). Using this technology, companies have also created a miniature pressure sensor or altimeter (15). In addition to their smaller size, MEMS pressure sensors also offer better performance. We used the Bosch BMP390 for this investigation, which can measure height differences with a margin of error of ± 5 cm (16).

In this study, we focused on determining a caller's vertical height using established techniques, which use sensors found in most smartphones. We identified the pros and cons with each technique, and although all of them have the potential to measure vertical height, only some were suited for use in a high-rise building whereas others were more appropriate for outdoor use or in buildings with non-uniform layouts, such as a mall. We also found that compensating for error sources is key for applying these location techniques successfully. We were able to estimate floor level reasonably well using the MEMS pressure sensor, which can provide valuable information to emergency services in urban locations.

RESULTS

The goal of this study was to determine the best way to estimate a person's floor level in a building using sensors commonly available in smartphones and additional publicly available data (17). We used a MEMS pressure sensor from Bosch connected to a Raspberry Pi and an iPhone 13 with built-in GPS, magnetic sensor, and WiFi receiver for our experiments. We conducted the experiment by taking sensor readings on multiple floors of a high-rise building on two separate days (**Figure 1**).

We were able to clearly differentiate the floor based on either GPS or pressure sensor readings, so either of these sensors had enough resolution to be of actual use (**Figure 2**). GPS offered the most direct way of measuring vertical height without the need for any additional processing of the sensor data; however, we saw an average height error of 10.4 m based on our location on a given floor (**Figure 2**). Assuming a floor height of 3.65 m, this average error corresponds to nearly three floors. However, this is not due to the inherent accuracy limitation of GPS. For comparison, the error reduced to 3 m when measurements were made in a balcony that allowed better satellite reception. The pressure sensor offered the most repeatable data without the need to communicate with other equipment, e.g. satellite or WiFi

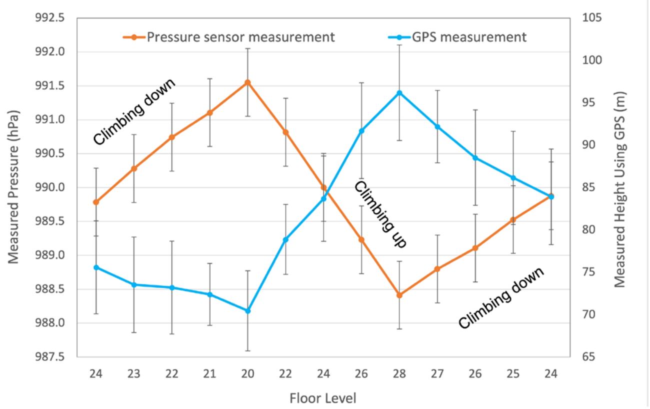

Figure 2: Pressure and GPS measurements on different floors of a high-rise building showing clear separation between floors. This dataset is from trial 2 and each datapoint represents an average of 10 sensor readings. We can see a clear trend in the sensor readings with respect to vertical height for both GPS and the pressure sensor. However, the MEMS pressure sensor readings were more linear in contrast to the GPS data, suggesting better repeatability.

router. The altimeter's measurement error was 0.7 Pa or 6 cm, which is much smaller than the typical floor height of 3.65 m. These measurements indicated that the pressure sensor was precise enough to place the caller within a specific floor.

Although the height resolution and repeatability of the pressure sensor was much better than the GPS sensor, both sensor measurements varied considerably in separate trials. The average difference in GPS readings between the trials that were conducted in the same building on different days was 19.1 m or ~5 floors (**Figure 3**). The pressure sensor showed an average difference of 1210 Pa which corresponds to a height of 101 m or nearly 27 floors (**Figure 3**). For GPS, we also noticed measurement drift within trials. The average difference in readings between the first and last measurement on floor 24 was 7.1 m with the GPS, but as low as 0.8 m with the pressure sensor. This shows that the pressure sensor is more stable over time.

While our results showed the feasibility of using the pressure sensor or GPS to estimate floor level, the errors identified made the sensor readings on their own impractical for an important application such as E911. We identified several ways of improving the pressure measurement. We first compensated for ground level height variation, which was the largest source of error in the measurement. For example, the 30th floor of a high-rise in Denver will have a very different air pressure reading compared to the 30th floor in Los Angeles. This is because Denver sits 1609 m above mean sea level versus 87 m for Los Angeles. Since we were only interested in the floor level irrespective of the building's location, we needed to subtract the ground level pressure from our reading; this value would act as our local reference point to calibrate our measurements, regardless of location. We obtained the ground level pressure for our study from the nearest weather station (17). Next, the ground level pressure does not stay constant over time; atmospheric conditions such as rain strongly affect the ambient pressure. For example, according to the data recorded from a weather station at Midway Airport in Chicago, the range of atmospheric pressure variation in the city over a 1-month period was 5500 Pa, which translates to almost 468 m of height difference (18). However, we can account for this variation by comparing the sensor's measured pressure with the pressure obtained from the weather station. This will help compensate for both location and weather conditions. After compensating for atmospheric pressure, the error reduced from 101 m to <2 m between trials (**Figure 4**). We compared the estimated height from the pressure sensor and GPS to the actual height of the floor level. We were able to estimate floor level to within ±1 floor using the pressure sensor (**Figure 5**).

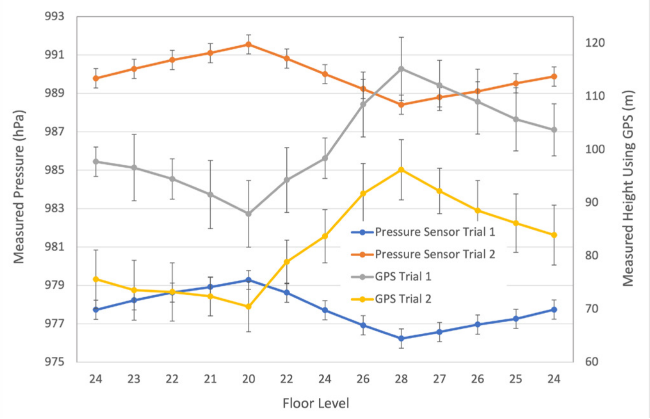

Figure 3: Pressure and GPS measurements on different floors of a high-rise building repeated on two separate days. Although the trend with vertical height was maintained, changes in weather caused a difference in pressure readings between the trials of 1210 Pa which corresponds to a height of 101 m. GPS showed an average difference of 19.1 m between the two trials. GPS also drifted within a single trial creating a difference in readings between the first and last measurement on floor 24 of 7.1 m on average.

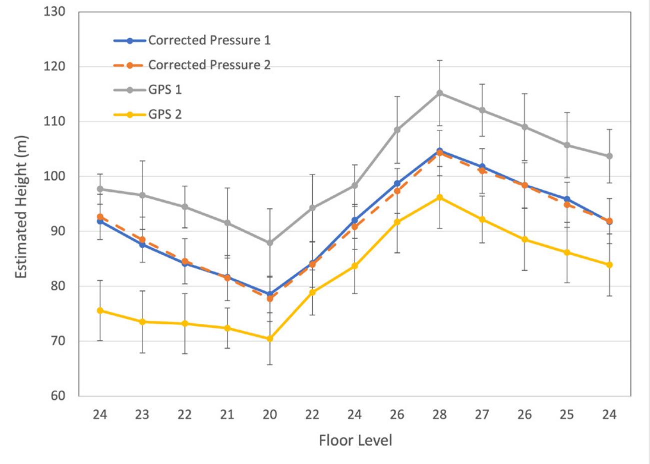

Figure 4: Height estimation based on pressure measurement at each floor after compensating for local atmospheric pressure and the location of the building. After compensation, the pressure sensor error reduced from 101 m to <2 m between trials. Since GPS provides a direct measurement of height, we could not find any way of compensating for error sources through calculation.

The magnetic sensor and WiFi measurements did not show a direct correlation to vertical height. Additionally, the WiFi signal dropped significantly within one floor of the router location. WiFi signals have a range of ~45 m but were weakened severely by the building structure, so we could not get any signal beyond 1 floor above or below the router location. The magnetic field measurement did not show a clear correlation to floor level. In addition, the field measurements in different floors were not unique (**Figure 6**).

DISCUSSION

The goal of this study was to determine the best way to estimate a person's floor level in a building using sensors commonly available in smartphones and additional publicly available data such as local atmospheric pressure, elevation from sea level, and building height (17).

In our study, we used a simple approximation of building height divided by the number of floors, which is not always accurate. In addition to external error sources, we also need to consider the absolute accuracy of the pressure sensor, which is ±50 Pa over the operating temperature and pressure range. This translates to ±4.16 m of height error which is larger than the typical floor to floor distance of 3.65 m. Narrowing a person's location down to 3 or 4 floors is still significantly better than first responders knowing nothing concerning a person's whereabouts in a high-rise. This study shows that although the sensor performance is sufficient for the target application, the error compensation is much more important and needs to be carefully considered to make the system

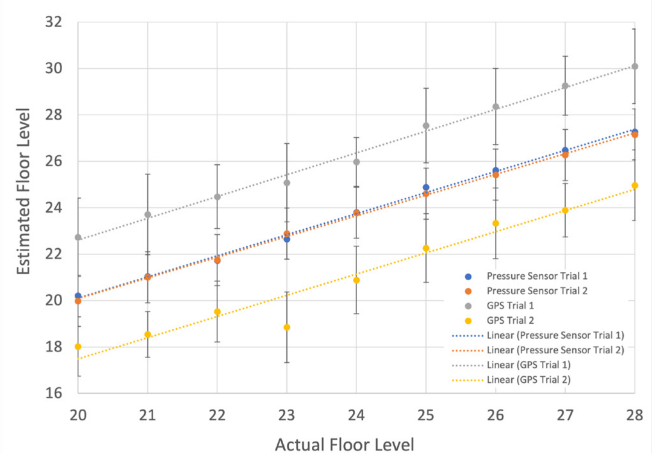

Figure 5: Estimated versus actual floor level using different techniques. Each data point represents an average of 10 sensor readings. These data show that the MEMS pressure sensor, although it is an indirect way of measuring vertical height, can be more accurate than the GPS after error compensation.

usable.

GPS accuracy depended on the signal strength, and the reception inside the building was generally poor. As the GPS signal decreased, the height measurement error increased because the GPS could not determine the exact location. This is one of the reasons GPS is not often used for locating people indoors. GPS provides a direct measurement of height, so we could not find any way of compensating for error sources through calculation. GPS has several known error sources, including atmospheric refraction and multi-path interference (19). Atmospheric refraction is a phenomenon where radio waves get refracted by Earth's ionosphere and troposphere, which causes the speed of the GPS signal to be different from the speed in space, introducing errors into the distance calculation. Multi-path interference is when GPS signals bounce off reflective surfaces; this is especially common in cities and inside buildings. Unfortunately, there was no way for us to compensate for these error sources.

We found that both WiFi and magnetic field mapping were not suitable for floor level determination in a high-rise. A previous study, however, presented these techniques as suitable methods for locating people in a mall (20). A typical mall has a broader footprint versus height, and different floors have a unique and open layout that is more conducive to magnetic field mapping. Typically, a single WiFi network is deployed throughout the space, with numerous routers or access points to make up for the short range of WiFi signals. In contrast, a typical high-rise, especially residential, has a repeating layout of stairs, doors, elevator locations, structural columns, etc. from one floor to the next, which makes the magnetic field mapping technique less effective since multiple floors will have the same signature. For our study, we could only access a WiFi signal from our home network, which had an extremely limited range of just one floor.

Overall, we found that pressure sensors provided a relatively simple and accurate way of determining floor level, and it did not rely on communication with a satellite or WiFi router. This type of system, with improvements, could help emergency services get to a person in need even faster, and eliminates the risk of a person not being able to tell 911 where they are in a building (21-22). Future studies can focus on several remaining questions to make the system more robust. We need to repeat this study in several buildings, ideally in different cities with varying altitudes above sea level. We need to account for the differences in atmospheric pressure between the weather station and the building, which can be several kilometers apart. We also need a better way of estimating the floor level than simply assuming an average floor height.

MATERIALS AND METHODS

Hardware Configuration

For this study, we used a MEMS barometric pressure sensor BMP390 manufactured by Bosch. The sensor has a measurement range of 300–1250 hPa (standard atmospheric pressure is 1013.25 hPa). The sensor outputs data in digital format using the I2C protocol, so an interface board was used to connect the sensor to a Raspberry Pi. The Bosch sensor offers several operating modes that trade-off performance for power. We used the highest performance mode that was the least noisy. We also used an iPhone 13 for our experiments that has built-in GPS, magnetic sensor and WiFi receiver and used the Physics Toolbox app to record and export data from these sensors.

Pressure Sensor Data Processing

The first step in calculating the floor level was to convert the sensor output that was in units of pressure to vertical height or altitude. As part of the conversion from pressure to height, we could compensate for the location and weather conditions by using the local atmospheric pressure as the ground floor reference (12). We then calculated the average floor height:

$$Average\ Floor\ Height = \frac{Building\ height}{Number\ of\ floors}$$

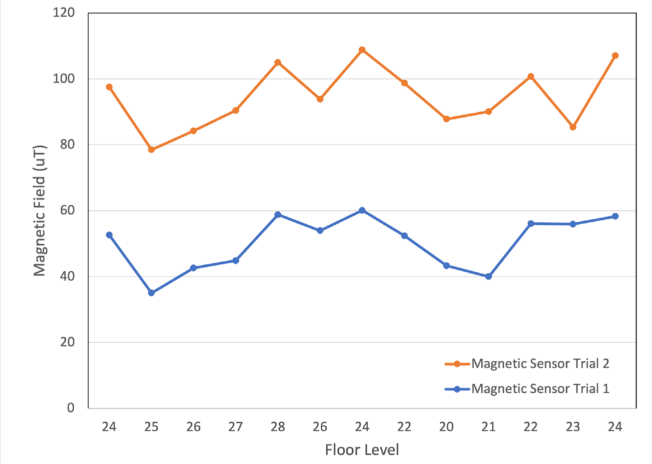

Figure 6: Magnetic sensor measurements on different floors of a high-rise building repeated on two separate days. Unlike the pressure sensor and GPS readings, the output of the magnetic sensor is not monotonically increasing or decreasing with floors–there is no clear trend that can be derived. The measurements do not seem repeatable as the data were not consistent between the two trials, even though the magnetic field should not be influenced by weather changes.

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And finally, the estimated floor level:

$$Estimated\ Floor\ Level = \frac{Altitude}{Average\ Floor\ Height}$$

Experimental Procedure

The study was conducted in a high-rise building in Chicago, IL. The sensors were configured to record multiple samples on a given floor and the measurements were repeated on eight floors. We started on floor 24, and went four floors below and four above, stopping and recording each individual floor's data and finishing on floor 24. However, during the climb between the lowest and highest floor, we skipped every other floor. So, the floor sequence was 24, 23, 22, 21, 20, 22, 24, 26, 28, 27, 26, 25, 24 (**Figure 1**). The reason for starting and ending on the same floor as well as going above and below the initial floor was to see if the measurements were repeatable on a given floor over time. We performed two trials on two separate days, each day repeating the same floor sequence and recording sensor outputs.

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