Monitoring Building Door Events using Barometer Sensor in Smartphones

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ABSTRACT
Building security systems are commonly deployed to detect intrusion and burglary in home and business structures. Such systems can accurately detect door open/close events, but their high-cost of installation and maintenance makes them unsuitable for certain building monitoring applications, such as times of high/low entrance traffic, estimating building occupancy, etc. In this paper, we show that barometer sensors found in latest smartphones can directly detect the building door open/close events anywhere inside an insulated building. The sudden pressure change observed by barometers is sufficient to detect events even in presence of user mobility (e.g. climbing stairs). We study various characteristics of the pressure variation due to door events, and demonstrate that door open/close events can be recognized with an accuracy range of 99.34% - 99.81% based on the data collected from 3 different buildings. Such a low-cost ubiquitous solution of door event detection enables many monitoring applications without any infrastructure integration, and it can also work as an augmentation to the existing expensive security systems.

Author Keywords
Barometer; Mobile Computing; Building Monitoring.

ACM Classification Keywords
C.5.3 Computer System Implementation: Microcomputers - Portable Devices; I.5.4 Pattern Recognition: Applications - Signal Processing

INTRODUCTION
Building security systems have become commonplace for protecting against intrusions and burglary in homes, offices and businesses. Currently, most prevalent form of building security system requires installing an electrical circuit on the periphery of doors to detect their open/close events. However, due to their high cost, these building security systems are undesirable for many simple monitoring applications, such as logging door open/close events, estimating building occupancy, times of high/low entrance traffic, etc. In fact, these needs of monitoring building door open/close events can be fulfilled with a barometer sensor in a latest smartphone, which requires no infrastructure integration.

In this paper, we provide an empirical evidence that the barometer sensor commonly found in latest smartphones can directly detect the building door open/close events anywhere inside an insulated building. This observation is based on the fact that most of the buildings are equipped with HVAC (Heating, Ventilating and Air Conditioning) systems to maintain a convenient indoor temperature and pressure. It uses a compressor to eject/absorb the air to/from the outside for ventilation, which creates a noticeable pressure difference between the indoor and outdoor environment. When a building door is opened, the sharp change of indoor pressure can be easily observed using smartphone barometer sensors. Once the door is closed, the HVAC system restores the pressure level allowing the detection of next open/close event. This surprisingly simple scheme has following advantages:

1. The pressure change can be observed by the smartphone barometer sensor from *anywhere* inside an insulated building. Even if the user takes her smartphone to a room hundreds of feet away from the building entrance or a conference room with closed room doors, the smartphone can still detect building door open/close accurately.

2. The pattern of pressure variation caused by door events is a good representative of the type of the building door. In a building with multiple types of doors (e.g. manual, automatic, etc.), it is possible to distinguish which door is opened by simply monitoring such changing pattern.

3. It is known that smartphone barometer readings can be affected even by small altitude variations due to user's movements. We show that our mechanism of door event detection is still reliable in the presence of user mobility such as walking, standing up, climbing stairs or taking elevator.

Based on these characteristics, we claim that smartphone barometer based door open/close detection enables a low-cost and ubiquitous building monitoring system that does not require any dedicated sensors to be deployed on each door. It can consequently augment the robustness of existing security systems. Besides, the detection of sharp pressure changes can trigger a direct notification on authorized user's smartphone which can be anywhere inside the building. This barometric

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pressure detection and its straightforward notification can also serve as an augmentation to many other applications such as estimating building occupancy, monitoring the usage frequency of entrances and exits, etc.

We exploit the data collected from 3 different university buildings and present that building door open/close events can be recognized even in the presence of user's mobility. It is shown that by analysing the pressure changing rate, it is possible to distinguish the door open/close events from others such as climbing stairs or taking an elevator.

RELATED WORK

Patel et al. [9] first exploited a HVAC air filter attached with pressure sensor units to detect pressure variation, and consequently proposed infrastructure mediated sensing, which relies on deploying additional instruments to the existing HVAC systems. The barometer sensor in smartphones is primarily valued for aiding the operations of other sensors. In [12], phone's Global Positioning System (GPS) was shown to benefit from the barometer sensor due to its faster altitude calculation. The barometer also contributes to revealing floor changes (through elevator or stairs) with almost 100% accuracy as shown in [8]. Moreover, since it has a better performance in detecting vertical activities than accelerometer, [11] leveraged it for monitoring group movements across different floors of a building. Along the same lines, it was shown in [10] that by observing pressure changes through barometers, it is practical to recognize whether a user is idle, walking or in a vehicle with little power consumption. Apart from these recent studies, there is a limited amount of work available on utilizing barometers for mobile sensing and ubiquitous computing. Work presented in this paper provides a new direction of how the indoor/outdoor pressure difference can be explored for mobile sensing.

There has been some recent work using various sensors to monitor the door open/close events. Authors in [6] proposed to attach vibration sensors to each door, which required additional communication mechanism to notify users in the building. Some commercial products such as [5] can detect an intruder by listening to the infrasound when a door or window in the range is opened. However, barometric pressure changes caused by door open/close can be detected anywhere inside the building and displayed directly on user's smartphone. This enables a low-cost solution for door event logging and building monitoring applications.

DETECTING DOOR OPEN/CLOSE USING BAROMETER

Our observations are based on the barometer sensors included in the latest smarphones (e.g. Nexus 5/6, Samsung Galaxy S5/S6, iPhone 6, etc.). Usually, they can contribute to aiding (1) GPS localization by faster altitude acquisition and (2) weather predictions based on pressure measurements. We apply two Google Nexus 5 [4] devices for our measurements. The devices use Bosch BMP280 barometer sensors [3] (also used in Apple iPhone 6 [2]), which have a pressure resolution of 0.01 hPa (hundred Pascals). We capture the barometer output on the Android phones using AndroSensor [1] mobile app at a sampling rate of 20 Hz.

Indoor Barometric Pressure - A Key Observation

In this paper, we are primarily interested in pressure measurements using smartphone barometer sensor inside insulated buildings with running HVAC systems. The HVAC system maintains a convenient indoor atmosphere by adjusting the air pressure and temperature. This results in a considerable difference between the pressure inside and outside the building. To demonstrate this, we place one smartphone on the ground inside the building and the other smartphone on the ground outside the building. To ensure that both the phones are at the same elevation, we place them at a distance of less than one meter but separated by a glass building wall. Fig. 1a shows the pressure measurements of both phones for a period of 24 hours. Although a long-term change is observed in both indoor and outdoor pressure, there is a constant difference between the indoor and the outdoor pressure (i.e. an average of 0.25 hPa for the chosen building).

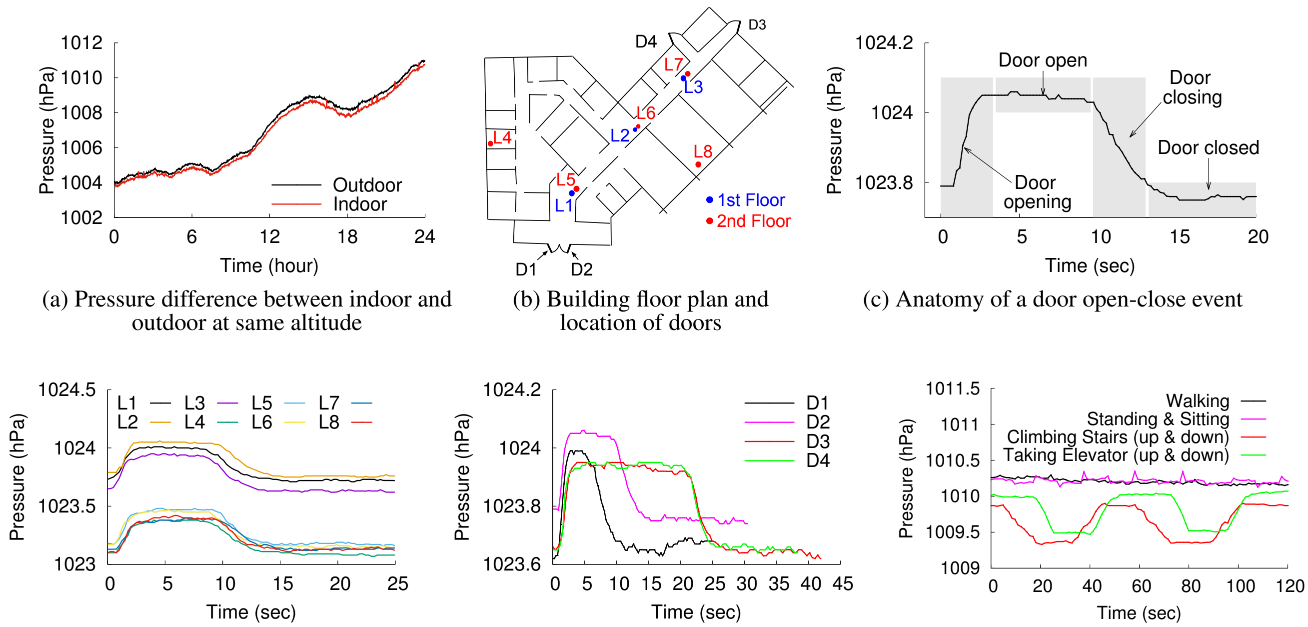
When a building entry/exit door is opened, a sudden increase in the indoor pressure is observed at the moment. This pressure increment can be measured by the smartphone barometer to indicate an occurrence of door open event. Once the door is closed, the HVAC system restores its original desired pressure and maintains it, allowing the correct detection of the next door open event.

Observations and Empirical Analysis

We now take a look at various characteristics of barometer-based door open/close detection. For illustration, we only use results of one building (a university building) in this section, and defer a more comprehensive analysis of multiple buildings in the next section. Fig. 1b shows the plan layout of the building. The building has 2 floors with 4 doors (D_1 to D_4 in Fig. 1b) at the first floor. Doors D_2, D_3 and D_4 are automatic which means that when they are pushed/pulled, they open to full 90^o and close automatically after a certain time. Door D_1 is manual and opens as much as user's pull/push and closes immediately.

Observation-1: *Smartphone barometer sensor can detect building door open/close events.* In the experiment, one smartphone is placed on the ground at location L_1 (Fig. 1b) and door D_2 is opened. Another smartphone is attached to the door D_2 itself to collect 3-axis accelerometer sensor data. The latter device provides true and precise time of (1) door-opening, (2) door-open, (3) door-closing and (4) door-closed events. Fig. 1c shows the barometric pressure changes recorded by the smartphone at L_1. It is observed that the pressure increases for the duration of the door-opening, remains constant for the duration of door-open, and then decreases as the door closes. The indoor pressure is restored after the door is closed completely.

Observation-2: *Smartphone barometer sensor detects door open/close events anywhere inside the building.* To observe this, the smartphone is placed on the ground at 8 different locations (L_1 through L_8 in Fig. 1b). Locations $L_1 - L_3$ are at first floor, while $L_4 - L_8$ are at second floor. Especially, L_4 and L_8 are chosen to be inside the offices with the office doors closed. The pressure observations are shown in Fig. 1d, where the variation caused by opening D_2 is identical for all



(a) Pressure difference between indoor and outdoor at same altitude

(b) Building floor plan and location of doors

(c) Anatomy of a door open-close event

(d) Pressure variation due to D_2 event at different locations

(e) Pressure variation due to opening different doors at location L_2

(f) Observed pressure changes for different user activities

Figure 1: Understanding the characteristics of pressure variation due to door open/close event

8 locations, and the pressure changes are not only observed in corridor locations but also inside the closed offices. Note that a distinct baseline pressure difference is observed as expected because of the floor elevation difference.

Observation-3: *Pressure variation pattern depends on the type of the opened door.* Fig. 1e shows the pressure readings at location L_2 while opening the doors D_1 through D_4. It is observed that the pressure changes of opening D_3 and D_4 (identical automatic doors) is also identical. However, the pressure change pattern is clearly distinct for D_1, D_2 and D_3/D_4 since they are different types of doors. This means that pressure variation pattern can also allow us to distinguish between different (types of) doors.

Observation-4: *Pressure variations due to door open/close events are distinguishable from those caused by user's movement and mobility.* Fig. 1f shows the pressure variations due to common indoor activities meanwhile the user keeps the smartphone in her pant pocket. It is observed that pressure variations due to walking as well as repeatedly standing and sitting exhibit only minor pressure changes (because of minor altitude changes). On the other hand, pressure variation pattern for climbing stairs or taking elevator (up and down) seems similar to that of door open/close, however, the rate of pressure change is much slower for stairs and elevator. We will present in the next section that relying on characteristics such as rate of change, mean-crossing and standard deviation, it is practical to distinguish door open/close events from such user activities.

NUMERICAL EVALUATION

In this section, we collected the data from 3 different university buildings, and used them to train and evaluate a machine learning classifier that can detect the door open/close event with high accuracy. The structure information of three university buildings in consideration is listed in Table 1. For Building-1, we recorded the door usage by observing people entering/exiting through building doors, and we completed the experiments for rest two buildings with two participants volunteering for opening/closing doors. In all experiments, the pressure readings were recorded on user's smartphone. The user moved around freely over the time of the experiments, frequently taking the stairs or elevator. We manually recorded the number of times any door was opened in a building to create the ground truth for verification. During the time of the experiments, doors were observed to be open/closed 30-50 times for each building.

	Building-1	**Building-2**	**Building-3**
No. of Doors	6	4	4
No. of Floors	3	2	2
No. of Rooms	80	76	23
Area (sq.ft.)	43,930	47,823	11,326

Table 1: Structure information of three buildings

Feature Selection and Detection Accuracy

In order to accurately detect the pressure changing pattern caused by door open/close events, we use a sliding window based approach. The size of the sliding window is chosen to be 3 seconds to accommodate complete door openings. Barometer readings are collected at 20 Hz sampling rate. For the 3-second time window, we calculate the following three features. (i) Rate of change: this feature indicates the rate at which the pressure changes during the window. User activities such as walking, sitting/standing and even climbing stairs are likely to result in slower rate of pressure change

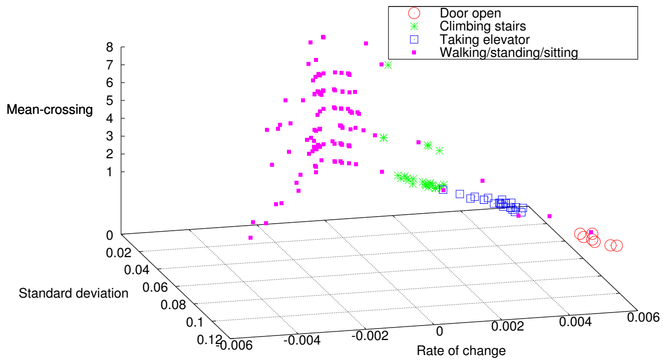


Figure 2: Rate of change, standard deviation and mean-crossing of pressure readings can distinguish different events and activities

compared to door open/close events. (ii) Mean-crossing: the rate of change does not capture how many times sudden variation of pressure was observed. To address this, we measure the number of times observed pressure crosses the mean pressure of the window. This allows us to distinguish door open/close, climbing stair and taking elevator events (mean-crossing values close to 1) from the rest of the user activities. (iii) Standard-deviation: it captures the general variation around the mean pressure of the window to further improve the detection of user's activities on the same floor (i.e. walking, standing, sitting).

Fig. 2 illustrates how these 3 features together enable the recognition of different activities. The rate of pressure change due to door open/close is faster than that caused by climbing stairs and taking elevators. The proposed three features have shown to be sufficient to classify the user activities and events. For continuous detection, the features are calculated every half a second for the pressure readings of last 3 seconds.

We build and train a machine learning classifier that uses the three features to detect the door open event. Due to the simplicity of feature space, Naive Bayes classifier (using Weka [7]) is used as the machine learning algorithm. We build a separate classifier for each building, because a user is likely to be interested in detecting the door events for her own home or business. Table 2 reports the True Positive (TP) rates and False Positive (FP) rates of door opening event detection for 3 buildings in consideration. It demonstrates that door opening event can be classified with an accuracy range of 99.34% - 99.81% using the 3 features we described above. Table 3 provides the results on 4-class classification where the door "not opening" is further divided into (i) climbing stairs, (ii) taking elevator and (iii) walking, sitting or standing activities. The TP rate of door opening detection reaches 100% in this case. The climbing stairs and taking elevator events are often misclassified which is expected, given that these events lead to lower rates of change and have less distinction between each other compared to door open/close events.

	TP Rate	FP Rate
Building-1	99.81 %	0.19 %
Building-2	99.34 %	0.66 %
Building-3	99.73 %	0.27 %

Table 2: TP and FP rates of binary classification (door opening or not) for 3 buildings

Event/activity	TP Rate	FP Rate
Door opening	100 %	0 %
Climbing stairs	93.6 %	1.8 %
Taking evevator	87.0 %	0.3 %
Walking/sitting/standing	97.8 %	3.9 %

Table 3: TP and FP rates of 4-class classification for Building-3

DISCUSSION

Our results confirm that the pressure variation caused by door open/close events can be detected anywhere inside the building by the barometer on user's smartphone. The advantage of this technique is that it relies on *pressure difference* instead of the absolute pressure values, making it applicable regardless of locations with different altitude levels and weather variations. We have used one type of smartphones in our experiments, however, as mentioned in [8], barometric sensors in different phones only have a constant difference (small error) in absolute value readings but their pressure variations are identical.

We demonstrated this phenomenon in 3 insulated university buildings equipped with HVAC systems, which are common settings in office buildings as well as some homes and restaurants in developed countries. Since the HVAC system is required to maintain the indoor/outdoor pressure difference, the application of our work has following limitations.

- The detection highly relies on building's HVAC system configuration. If the HVAC system is periodically turned off depending on the requirement and weather conditions, the detection accuracy can reduce.
- The detection of door open/close events also depends on the pressure difference recovery from the previous one. The following event detection can fail if the door is re-opened immediately before the system has rebalanced or more than one door is opened at a time.
- In many other buildings (e.g. hotels), individual rooms use opening windows or their dedicated air conditioning units with or without central HVAC systems. These cases require further exploration since it is not clear whether our technique can detect door events in such circumstances.

CONCLUSIONS

The core conclusion of this paper is that barometric pressure variation observed in smartphone barometer sensor can be used to detect door open/close events anywhere inside an insulated building. Note that the aim of the work was not to develop a comprehensive system for building security, but it was to empirically demonstrate the potential and limitations of barometer sensor in smartphone for the purpose of activity monitoring and building safety applications. It can be concluded that barometer-based door event detection can serve as an augmentation to the existing building safety applications without any infrastructure integration.

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