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6 authors, including:

Fowzia Akhter
Macquarie University

Sam Khadivizand
Macquarie University

Md Eshrat E Alahi
Walailak University

S.C. Mukhopadhyay
Macquarie University

Design and Development of an IoT enabled Pedestrian Counting and Environmental Monitoring System for a Smart City

Fowzia Akhter[1*], Sam Khadivizand[1], Jordan Lodyga[1], Hasin Reza Siddiquei[2], Md. Eshrat E. Alahi[3], S.C. Mukhopadhyay[1]

1. Dept. of Engineering, Macquarie University, Sydney, Australia
2. Dept. of Electrical and Electronic Engineering, Uttara University, Dhaka, Bangladesh
3. Shenzhen Institute of Advanced Technology, Chinese Academy of Sciences, Shenzhen, China

e-mail: fowzia.2k3@gmail.com

Abstract—**A novel method for pedestrian counting using passive infrared (PIR) sensors is proposed and the corresponding system has been designed and developed. The inclusion of an environmental combo sensor in the proposed pedestrian counting system enabled environmental monitoring such as temperature, humidity, pressure, Carbon di Oxide (CO_2) and Total Volatile Organic Component (TVOC). The detection lengths of the PIR sensors are varied by tuning the Field of View (FoV) of the Fresnel lens to differentiate the movements of humans and animals. A novel method is applied to locate the PIR sensors in the designed mould so that their coverage regions do not overlap. The sensor data are transmitted to the Thingspeak server via Long Range Wide Area Network (LoRaWAN) communication protocol. The system is powered by a 6000 mAh rechargeable battery which is charged by the solar panel during day time enabling continuous data collection. The system's results are validated against manual counting and it is seen that more than 90% accuracy can be achieved by this intelligent system.**

Keywords-pedestrian count; environmental monitoring; smart city; PIR sensors, FoV

I. INTRODUCTION

With the burgeoning technical developments around the world, the idea of developing smart cities has been emerging over the last decade [1-2]. Due to the rapid growth of the population, the world is facing a threat of a shortage of available non-renewable resources [3]. That's why smart systems are developed where the infrastructures of the cities are integrated with intelligent devices to monitor and control the resource consumptions and environmental parameters via the Internet of Things (IoT) platform as shown in Fig. 1. This enables the city planner to understand the current trend, future demand and necessary planning to be done to ensure a sustainable lifestyle for the residents. IoT connects millions of sensors that are individually used for monitoring various applications over a range of disciplines. The growth of the use of the IoT, along with connection purposes, has also served the processing and storage of the obtained data in the cloud. These data will have a significant impact on city planning to improve the quality of life of human beings. Therefore, people counting in the office building, as well as public places is an active research area nowadays. There is significant research that has been carried out on human counting at the indoor environment [4-6] using different technologies such as video cameras, thermal cameras, pyroelectric (PIR) sensors, RFID and Wi-Fi probe requests [7-10]. Some of the major cities of the world have already adopted these technologies to develop their pedestrian counting systems. The systems developed by Auckland (New Zealand), New York (USA), Dublin (Ireland) and Liverpool (Australia) uses the video camera to find the number of people in each frame by counting heads or faces based on the applied image processing algorithm [11-15]. However, the system performance degrades due to variation of environmental parameters such as sudden darkness and angle of view of the camera. Moreover, this costly and complex system also violate pedestrian's privacy concerns [16]. This maximum accuracy achieved using this technique at an indoor environment is 95% whereas for outdoor application the value is 85% [17].

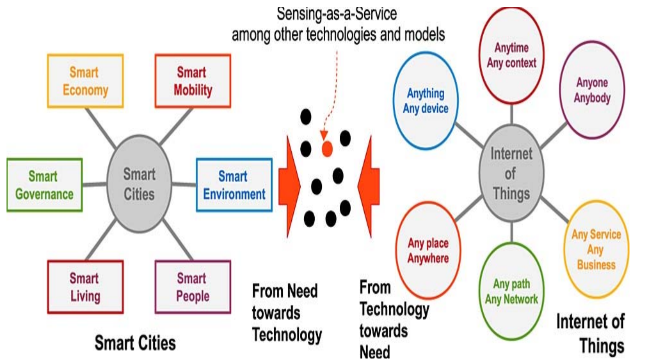


Figure 1. Schematic diagram depicting the relation between smart cities and the Internet of things [3].

The system developed by Melbourne City Council, Australia used the Infrared (IR) camera for pedestrian counting [18]. This type of camera detects IR radiation from human or animal. Later, this optical signal is converted into an electronic signal. This technology is useful for night-time surveillance compared to the video camera. However, it provides incorrect results because of occlusions or closing texture [19]. Moreover, the camera is not handy and consumes high current. Therefore, it requires the inclusion of amplifiers to drive by a microcontroller-based system [20].

PIR sensors are other important technology that has been extensively used for human detection in the indoor environment [21-22]. These low-cost, low-power passive sensors respond when an infrared (IR) emitting subject such as (humans or animals) passes through the FoV of Fresnel lens [23]. Usage of PIR sensors does not violate human privacy, unlike the video camera. The voltage supply needed to drive these sensors are 3.3~5V and current consumption is only 3 mA current while active [24]. Therefore, a microcontroller-based intelligent system is possible to develop using this sensor. The drawback of the sensors is that their performances deteriorate due to variations in temperature and humidity.

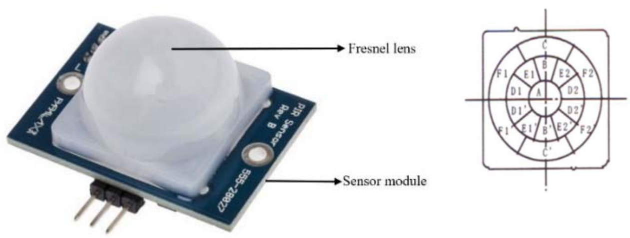
PIR sensors are chosen to use in this research due to its several advantages compared to other existing technologies. This paper presents a novel compact system that provides number of pedestrian as well as environmental parameters including temperature, humidity, pressure, CO_2 and TVOC. The detection lengths of the PIR sensors have been tuned to detect human movement only while neglecting the movements of domestic animals (dog, cat, etc.). A novel method is applied while developing the system to ensure no overlap among the detection regions of the PIR sensors. An intelligent algorithm is developed to convert pedestrian detection into pedestrian count to provide highly accurate results, more than 90% accurate compared to manual counting.

II. Materials AnD Methods

This section presents the methods of pedestrian detection and counting. It also explains procedure followed for transmitting data from the sensor node to the cloud server.

A. Method of Pedestrian Detection using PIR sensors

PIR sensors are used for pedestrian counting in this research. A PIR sensor is composed of a Fresnel lens and two sensing components. When IR emitting subjects such human or animal passes through the FoV of the Fresnel lens, the Fresnel lens focuses the IR radiation to one of the sensing elements. This causes the potential difference between the sensing elements. Fig. 2 (a) represents the PIR sensor module used in this research and Fig. 2 (b) shows the different sub-lenses of the Fresnel lens.



(a) (b)

Figure 2. (a) PIR sensor module and (b) A-F sub-lenses of Fresnel lens.

The FoV of the Fresnel lens is divided into A-F sub-lenses. Different sub-lens offers different detection lengths. The detection lengths of a sub lens may also vary for operating the sensor at full and reduced sensitivity mode. Fig. 3 shows the detection lengths of each sub-lens of Fresnel Lens at full sensitivity and reduced sensitivity. The sensor is calibrated and the values shown in Fig.3 are experimentally verified.

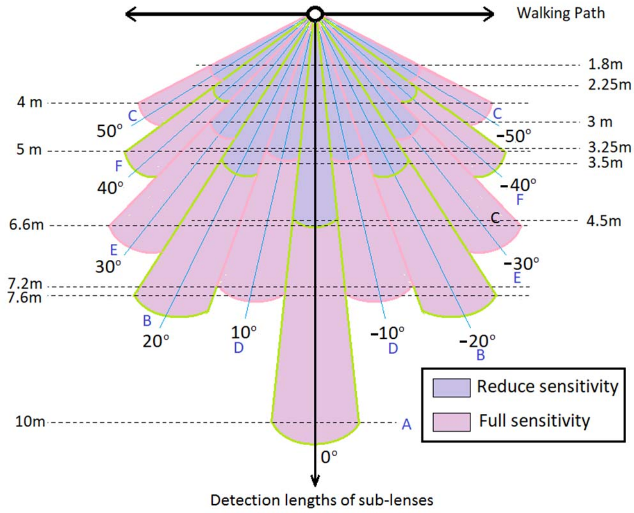


Figure 3. Field-of-view (FOV) of the Fresnel lens.

The objective of this research is to cover maximum 3m wide footpath and detects only human and overlook the movements of pets. Thus, the detection limit is reduced to 1m from the ground which is the maximum height of a pet dog in Australia [25]. Fig.4 (a), (b) and (c) shows the two-dimensional view of the FoV of the three PIR sensors used to cover 3 m wide footpath. To find the appropriate installation height, it is assumed that the system is mounted at the 5m height of the pole as shown in Fig. 4(a). PIR1 is positioned at 00 from the y-plane allowing the system to detect a person walking adjacent to the pole. As each sub-lens of Fresnel lens offers 100 FoV, the maximum possible coverage region by this sensor can be calculated as follows:

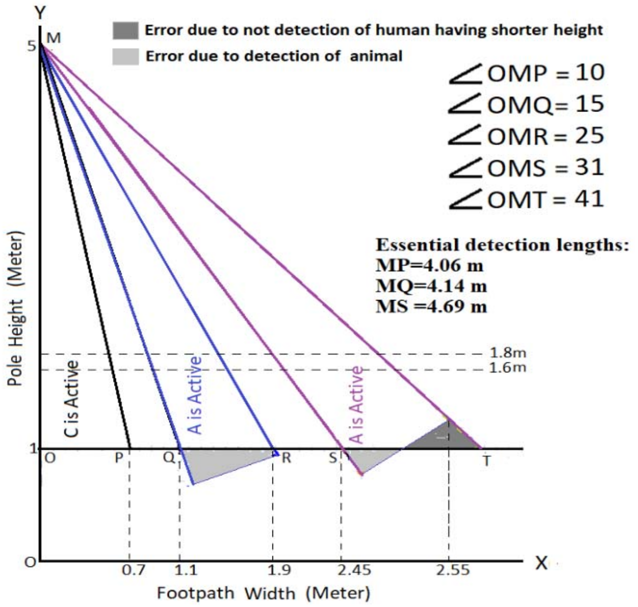
$$\text{Opposite} = \text{Adjacent} \times \tan\theta \tag{1}$$
$$\Rightarrow \text{OP} = \text{OM} \times \tan\angle OMP = 4\text{m} \times \tan 10^0 = 0.70 \text{ m}$$

It is imagined that a person is standing at the edge of the detection region of PIR1 for finding a suitable position of PIR2. Therefore, the location of PIR2 should be chosen in such a manner that the person is detected by PIR1 should not be detected by PIR2 at the same time. Therefore, the detection region of PIR2 should start and end at 15^0 and 25^0 respectively from the y-plane. The minimum and maximum coverage regions of the PIR2 are calculated as follows:

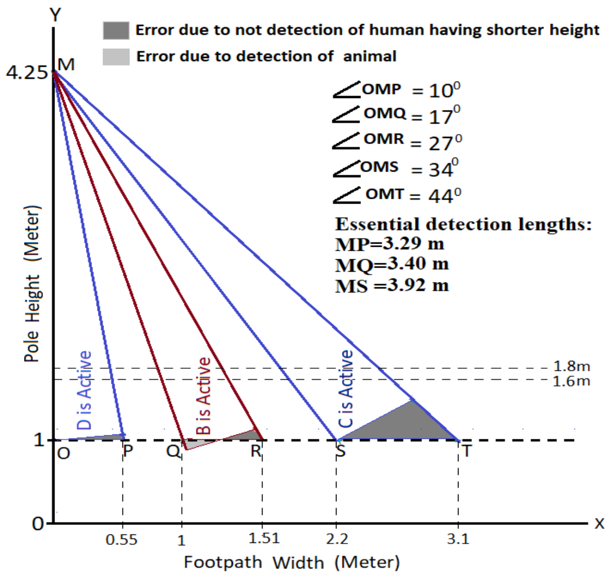
$$\text{OQ} = \text{OM} \times \tan\angle OMQ = 4 \text{ m} \times \tan(15^0) = 1.10 \text{ m} \tag{2}$$
$$\text{OR} = \text{OM} \times \tan\angle \text{OMR} = 4 \text{ m} \times \tan(15^0 + 10^0) = 1.90 \text{ m} \tag{3}$$

Similarly, coverage regions of PIR3 are calculated as 2.45m~3.47m. Due to keeping the gap between the detection regions no pedestrian would be detected twice. Therefore error can be minimized for walking patterns such as side by side.

The essential detection lengths (MP, MQ, and MS) by the PIR sensors are calculated as 4.06m, 4.14m and 4.69m, respectively using the formula of a right-angle triangle, such as, $hypotenuse = \sqrt{Adjacent^2 + opposite^2}$. Usage of sub-lens having higher detection length than the required one permits the detction of pets whereas usage of sub-lens having lower detection length than the required one disables counting pedestrians having the shorter height of 1.1m~1.2m. Hence, the selection of appropriate sub-lens of the Fresnel lens plays a vital role in error reduction. Fine-tuning is not possible due to using a commercial sensor. So, sub-lenses are selected that are nearest to the required one. Therefore, C sub-lens (4m) is operated as an active region for PIR1 and A lens (4.5m) is operated for PIR2 and PIR3. PIR1 is operated at full sensitivity, whereas the PIR2 and PIR3 are operated at reduced sensitivity. Due to using the lens, some error will occur and those are shown by light gray and dark gray colour triangles. The areas of the triangles are calculated. The summation of the areas of the triangles is the total error region for this scenario and the value is 0.21 m².



(a)



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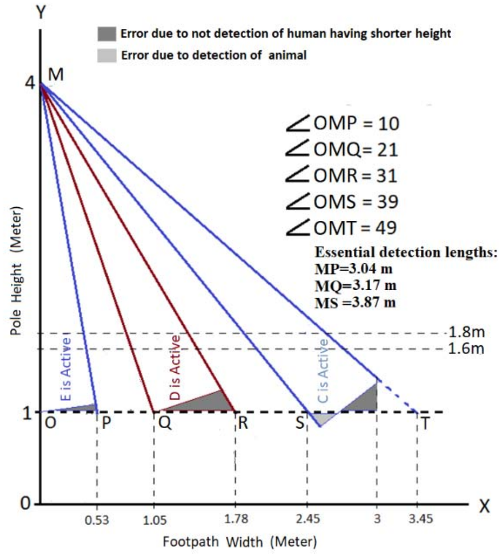


(c)

Figure 4. The selection of installation height of the sensor node.

It is also assumed that the system is mounted at 4.25 m and 4 m height of the pole and the same procedure is followed to find out the total error region. The values are shown in Table I. Simulation results show if the node is installed at 4m height, the error percentage will be less compared to other scenarios. Therefore, the final prototype is developed based on the calculations of that simulation.

TABLE I. COMPARISON BETWEEN ERROR REGIONS FOR THREE DIFFERENT INSTALLATION HEIGHTS

Position of the prototype at pole	Error area in detection region 1	Error area in detection region 2	Error area in detection region 3	Total error region
5m	0 m²	0.014 m²	0.07m²	0.21m²
4.25 m	0.1m²	0.03 m²	0.18 m²	0.31 m²
4m	0.025 m²	0.08 m²	0.05 m²	0.155 m²

B. *Algorithm of the Proposed System*

An intelligent algorithm is developed to count the number of pedestrians using PIR sensors. The time required to cross (T_C) the coverage region of a PIR sensor by a human is compared with the duration a PIR sensor remains at HIGH state (T_H) due to the detection of an IR source. From this comparative study, the number of pedestrians detected by each sensor is calculated. The summation of all the sensors count is the value of the total number of pedestrians. Due to applying this method, everyone walking in a line would be detected which reduces the probability of error.

During the starting of the office hours or weekend in the market places, people walk too close to each other. As a result, the sensor cannot switch between the states. Therefore, the application of this algorithm will prevent counting multiple people as a single in such a scenario. A counter variable is used to determine the number of pedestrians detected by a sensor. Initially, the value of the counter variable is defined as zero.

When the PIR sensor goes HIGH due to the detection of any human, the T_H is determined and the value of counter variables is calculated using the following steps. The average walking speed of a human, V_{avg} is 1.4 ms^{-1}[26]. The maximum detection length a PIR sensor is D_{Lmax}, then the value of T_C is calculated as follows,

$$T_c = \frac{D_{Lmax}}{V_{avg}} \tag{4}$$

If PIR1 remains at HIGH state for a duration of T_H, then the number of the pedestrian i.e. the value of a counter variable is calculated using this algorithm:

$$Counter_1 \approx \frac{T_H}{T_c} \tag{5}$$

The number of pedestrians detected by PIR2 and PIR3 is calculated similarly for 15 minutes. After that time, the value of a total number of pedestrians is calculated from the summation of the values of counter 1, 2 and 3. The Environmental combo sensor (Qwiic CCS811/BME280) data are also read. Later, all the sensor data are transmitted to the Thingspeak server via The Things Network (TTN) gateway every 15 minutes. Fig.5 shows the complete flow diagram of the developed system.

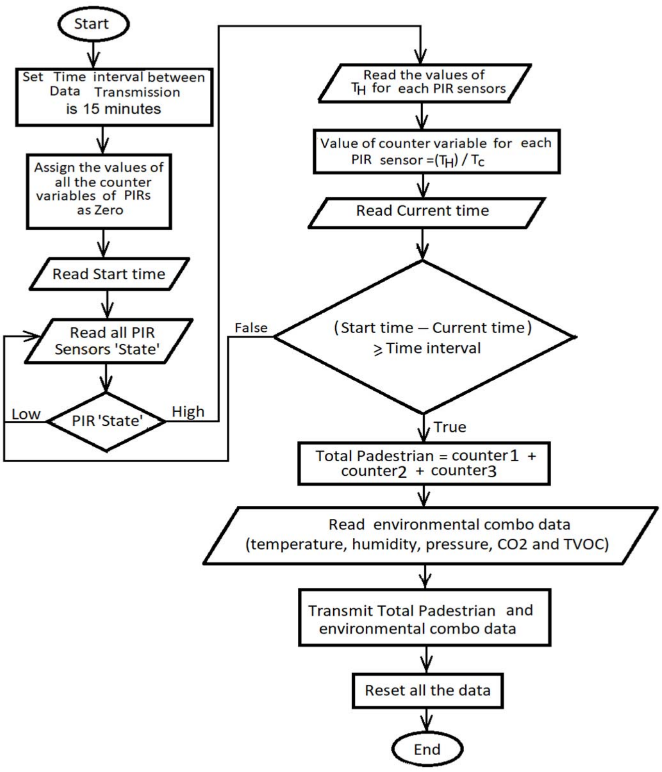


Figure 5. Complete flow diagram of the proposed system.

C. Developed of the Sensor Node

The sensor node is developed applying the method of pedestrian detection. A mould is designed using CREO Parametric 4.0 software to accommodate all the electronic devices. The front panel of the mould is a curvature shape so that the PIR sensors can be placed at the proposed angles. A small platform is also designed which can hold all the necessary electronics inside of the system as shown in Fig. 6 (a). The PIR sensors are placed inside the designed mould to protect those from direct sunlight which is shown in Fig. 6 (b). A holder is also designed for accommodating the environmental combo sensor which is connected to the mould. The sensor is placed in such a way that it is protected from rain but able to read the environmental parameters. The sensor node consists of PIR sensors and environmental combo sensor, Arduino UNO microcontroller, power converter, LoRa shield, rechargeable battery, and solar panel. This system is powered by a 6000mAh battery which is charged by 6V solar panel thus permitting data collection without any interruption. Two sensor nodes are developed initially. Those are mounted on the pole by pole brackets. The data collected from the sensor node are transferred to the Thingspeak server via Lora Communication protocol which is a low-cost, low-power communication protocol compared to other communication protocols. It offers connectivity up to 3 km and 10 km for urban and rural areas respectively [27] Fig. 6 (c) shows the study locations represented by yellow circles and Fig. 6 (d) shows the final system mounted on the electric pole.

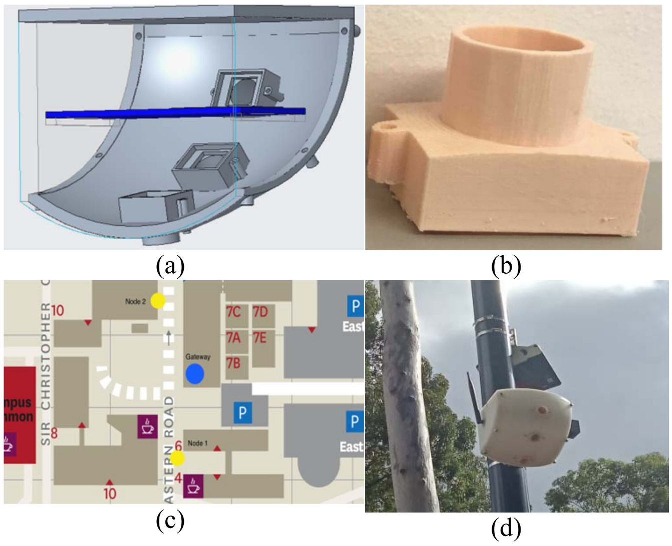


Figure 6. (a) 3-D design of the curvature (b) holder for PIR sensor (c) study location (d) final system mounted on the pole.

III. RESULTS AND DISCUSSIONS

Two systems are developed and installed on the electric poles of Macquarie University. Sensors data are stored on the Thingspeak channel for five consecutive working days (Monday-Friday) and the average data are considered for analyzing the systems' performances. The numbers of pedestrians crossing the coverage zone of the sensor nodes are counted manually from 8 am to 10 pm. It is chosen to start the manual counting at 8 am as this is the starting time of the offices as well as classes. So, the maximum number of pedestrians will be crossing the zone at this time. Therefore, the performance of the system in a crowded situation can be understood from the data. Manual counting is stopped after 10 pm because pedestrians are merely found after this time. Table II shows the comparative study of manual count and system count for the duration of 8:00 am-10:00 pm with a 1-hour time interval.

TABLE II. COMPARISON BETWEEN ACTUAL COUNT AND SYSTEM COUNT

Time	Actual count	System count	Error (%)
08:00-09:00	45	38	15
09:00-10:00	88	76	13
10:00-11:00	83	71	14
11:00-12:00	79	67	15.
12:00-13:00	99	85	14
13:00-14:00	106	93	13
14:00-15:00	83	70	15
15:00-16:00	74	63	14
16:00-17:00	52	45	13
17:00-18:00	46	40	13
18:00-19:00	29	24	17
19:00-20:00	16	14	12
20:00-21:00	18	15	16
21:00-22:00	9	8	11

The performance of the proposed system has been enhanced by comparing the manual count data with the system count data and finding the correlation between them (Fig. 7).

The equation for determining the actual count is obtained by linear fitting the curve which is presented as follows:

Total no. of pedestrian,

$$x = \frac{y+0.2276}{0.86}, \tag{9}$$

Where 'x' is the actual pedestrian count and 'y' is the system's count. This equation is used to normalize the values of system count of the final prototype.

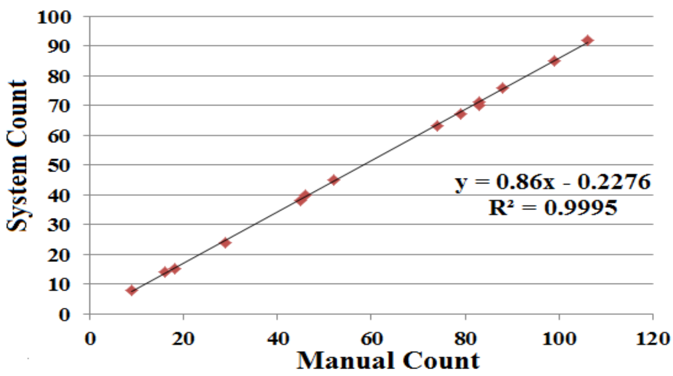


Figure 7. Relationship between the actual count and system count value.

The systems are re-installed on the electric poles after applying this error correction algorithm. System count and manual count data are compared similarly after re-installation. Table III shows corrected results of the system and the manual count values. It is seen from the tabular data that the probability of error is reduced to 10%.

Sensors data are stored in the Thingspeak cloud server which is an IoT platform that enables storing 8200 messages per day for free [28]. The interval of data transmission from the sensor node to the server is set to 15 minutes so that the battery sustains for a longer period. Fig. 9 shows the collected data represented in the Thingspeak channel from a system for a day. Six different fields of a Thingspeak channel are allocated to display the values of a total number of pedestrian, temperature, humidity, pressure, CO_2, and TVOC.

TABLE III. IMPROVED SYSTEM RESULTS WITH RESPECT TO MANUAL COUNT

Time	Developed system	Manual counting	Error (%)
08:00-09:00	62	67	7
09:00-10:00	111	115	3
10:00-11:00	59	64	8
11:00-12:00	93	99	6
12:00-13:00	88	94	6
13:00-14:00	72	78	7
14:00-15:00	84	89	5
15:00-16:00	69	73	5
16:00-17:00	103	109	5
17:00-18:00	86	92	6
18:00-19:00	52	56	7
19:00-20:00	37	40	7
20:00-21:00	11	12	8
21:00-22:00	19	21	9

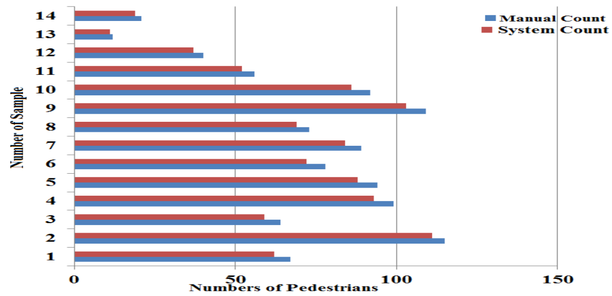
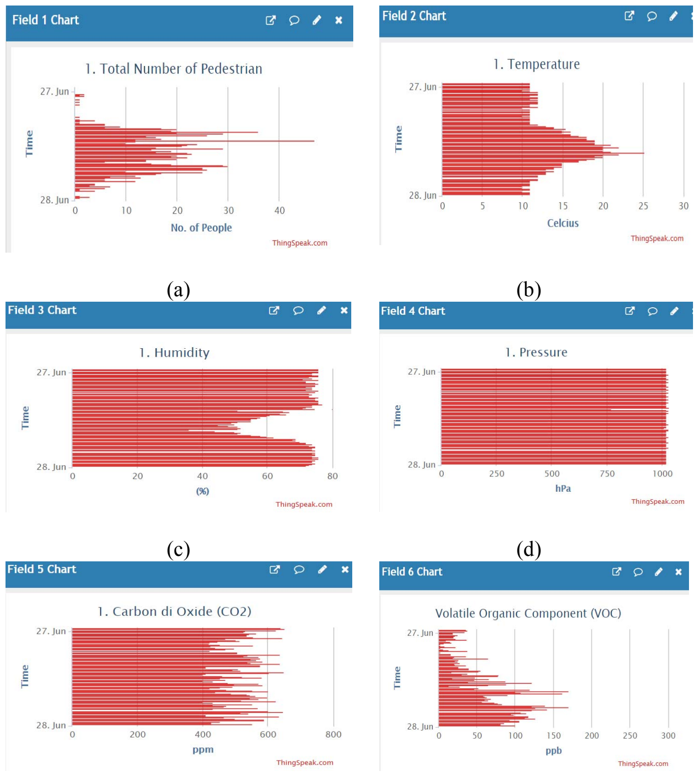


Figure 8. Comparison of manual count with the count from the developed system.



(a) (b) (c) (d) (e) (f)

Figure 9. Uploaded sensor data to the *Thingspeak* cloud server (a) Total number of Pedestrians (b) Temperature (°C), (c) Humidity (%), (d) Pressure (hPa), (e) Carbon di Oxide (ppm) and (f) Total Volatile Organic Component (ppb).

IV. CONCLUSIONS AND FUTURE RECOMMENDATIONS

Design and development methods of a novel pedestrian counting system using PIR sensors are thoroughly explained in this paper. The prototype is designed in such a manner that it can correctly determine the number of people walking side by side or walking in a line. It is also ensured by an intelligent algorithm that multiple people are not mistaken as a single individual. This developed system can distinguish the movements of humans and animals. The system is tested at peak and off-peak times of the day to understand it's performance during crowded and solitude situations. The system provides more than 90% accurate results. Moreover, the developed system is energy efficient due to employing low-power sensors as well as a low-power communication protocol. Installation of the system on the electric pole reduces the financial burden as well as does not change the infrastructure of the city. The addition of environmental combo sensors enables ambient monitoring which plays a vital role in urban planning. Therefore, it can be concluded that the developed sensor node is an energy-efficient, cost-effective compact system providing all the necessary features essential for a smart city application.

In addition to several advantages, there are some drawbacks of the proposed system which includes disability to detect human having a height less than 1 m. Therefore, babies sleeping in the stroller will not be detected. However, babies sitting on the stroller and people on the wheelchairs would be detected by the system.

Future work would be the collection of data for longer period and develop mathematical model for data prediction. The impact of environmental parameters on the pedestrian movement would also be studied. Some more important sensors would also be included to the system such as noise sensors and rain sensors.

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