2021 IEEE Global Conference on Artificial Intelligence and Internet of Things (GCAIoT) | 978-1-6654-3841-4/21/$31.00 ©2021 IEEE | DOI: 10.1109/GCAIoT53516.2021.9692929

Crowd Quantification with Flow Direction Estimation: a Low-Cost IoT-enabled Solution

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***Abstract*—Monitoring crowds in public environments is of great value for understanding human routines and managing crowd routes in indoor or outdoor environments. This type of information is crucial to improve the business strategy of an organization, and can be achieved by performing crowd quantification and flow direction estimation to generate information that can be later used by a business intelligence/analytic layer to improve sales of a specific service or targeting a new specific product. In this paper, we propose the design of an IoT Crowd sensor composed of an array of ultrasonic ping sensors that is responsible for detecting movement in specific directions. The proposed device has a built-in algorithm that is optimized to quantify and detect the human flow direction in indoor spaces such as hallways. Results have shown an average accuracy above 86% in the five scenarios evaluated when using an array with three elements.**

***Index Terms*—IoT, LoRa, Crowd Monitoring, Human Flow Estimation**

I. Introduction

Monitoring crowds in public environments is of great value for understanding human routines and managing crowd routes in indoor or outdoor environments. In the context of a pandemic, such as the one we are currently experiencing with COVID-19, a crowd quantification and flow direction estimation solution is even more relevant, since such solution helps to minimize physical contact between people by promoting effective social distancing, as defined in contingency plans that have been put forward by several organizations. For example, in an academic environment, such a system can be used for the redistribution of students, scholars, and staff in a balanced way throughout the built environment, i.e., hallways, courtyards, stairs, elevators, etc. In this case, it is expected to have several IoT Crowd Sensors distributed throughout the campus performing crowd quantification and estimating its flow direction. This information can then be transmitted to a cloud server, and heatmaps can be generated and accessed in real-time by the academic community. Additionally, this information can be sent back to specific IoT "traffic lights" (actuators) that are physically deployed on the campus, and thus allowing the implementation of crowd balancing across the environment. In this way, it becomes possible to alleviate their use and decrease the close contact that exists between students, scholars, and staff in times of pandemics.

Such a system will not only be beneficial during a pandemic but also useful for management purposes, for example in distributing the workload of students and scholars so that the waiting periods are minimized, i.e. canteen, bar, study rooms, etc. The goal is to improve an aspect that is found today in most academic environments or any other type of establishment frequented by customers, workers, or people in general, and which can be described as an improvement in the services delivered by an organization.

This paper is organized as follows: Section II introduces some relevant background; Section III introduces the overall system architecture; Section 4 is dedicated to the design and detailed implementation of the Monitoring System; Section 5 presents the demonstration of the results; and finally, in Section 6 the conclusions are presented.

II. Background

A. Related Works

Crowd quantification using sensors that allow the presence counting, detection of direction, and acceleration, allow the collection of relevant information that may be of great value for management purposes.

In [1], Grabowski et al. propose a method that can recognize information about queues, the emergence of flows on pedestrian roads, intersections of such flows, and other problematic situations, such as clogging. This information can help to optimize the management of public spaces, optimize schedule planning, improve personal provisioning, and reduce the probability of disasters during mass events. People flow detection focuses on the estimation and quantification of the direction of people in indoor or outdoor environments, such as hallways or pathways, and considering the two possible and opposite directions. According to the article by C. Wang and M. Tian in [2], in an entry/exit region, building managers should consider the increase or decrease of building entry or exit zones based on the collection and analysis of data related to the human flow on that specific entry/exit zones,

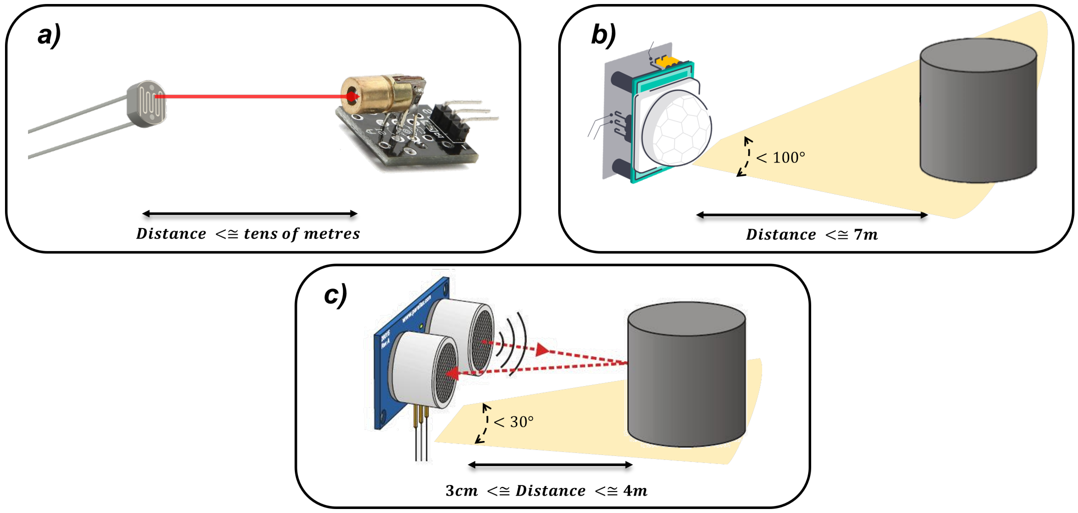

Fig. 1. Evaluation of possible approaches and low-cost sensor technologies for the implementation of the IoT Crowd Sensor.

i.e., based on the quantification of how many people are entering or leaving a building or region. In [3], Raza et al. present detection and tracking of moving objects or persons based on the HC-SR04 ultrasonic sensor. The proposed system uses an Arduino Uno board with a linear array of N=4 HC-SR04 modules. This application is intended to detect a moving human body and find its lateral direction of motion relative to the array line. Its accuracy approaches 96% for correct detection and direction-finding. The HC-SR04 ultrasonic sensor has a cost of approximately 2 €. In [4], several methods have been evaluated and explored for people counting in the context of the development of an IoT device for room occupancy monitoring. One of the evaluated methods consisted in using a long-distance Time-of-Flight sensor (VL53L1X). The VL53L1X long-distance Time of Light (ToF) sensor [5], can be used to count people crossing a specific predefined area and also describes an algorithm used to count people. In this case, the sensor is placed on the surface with direction towards the ground, whereas in the case of the previous projects the sensors would be placed diagonally and parallel to the movement of the people. The VL53L1X sensor can be used for counting people in multiple zones of the SPAD sensor's reception area, and configuring it with two different FoV, to alternatively obtain a variable distance between them and consequently recognize the movements of a person. Using a simple algorithm makes it possible to detect the direction in which a person crosses the predefined area. The VL53L1X sensor has a cost of approximately 20 €.

B. Sensor Technologies

To quantify and detect human movement, several low-cost technologies can be used. Figure 1 depicts the three more relevant low-cost technologies that have been identified for implementing the IoT Crowd Sensor. Note that, in our approach, we are focused on crowd quantification and in the human flow direction estimation, e.g. detection of the human direction in a hallway.

In Fig. 1a) a Laser-based approach is presented. Although very effective, without any obstruction in the light axis, it is possible to identify movement in a given space [6]. As a major disadvantage, a transmitter (Laser) and a receiver (Light Dependent Resistor — LDR) are needed, each one at different sides of the hallway, resulting in additional wires; it is also needed to be well-positioned and calibrated, since the Laser is highly directional. Secondly, in Fig. 1b), the PIR-based approach is depicted. A PIR (Passive InfraRed) sensor is specifically designed to signalize any movement based on the detection of emitted heat from objects. As a constraint, this technology covers a very large area and does not allow the direction of flow to be identified, because if more than one PIR sensor were used, the area covered by the two sensors would be too large and the area of interception between both sensors would still be large (FoV – a field of view of approximately 100º), which would lead to high measurement errors [7]. Lastly, in Fig. 1c), is illustrated the Ultrasonic-based approach. Although it has not been created to perform the function of detecting the direction flow of moving objects, it is possible to physically rearrange in an array format, so that through the difference in distances it is possible to compute not only crowd counting but also crowd flow direction estimation. Thus, the sensor can show itself as a better solution compared to the PIR, concerning the detection angle (FoV of approximately 30º), since the ultrasonic sensor is much smaller, and also presents itself as a better solution compared to the LDR sensor plus laser, since it does not require an emitter and receiver in two different locations or that they are so strict in their positioning, making it a portable solution [8].

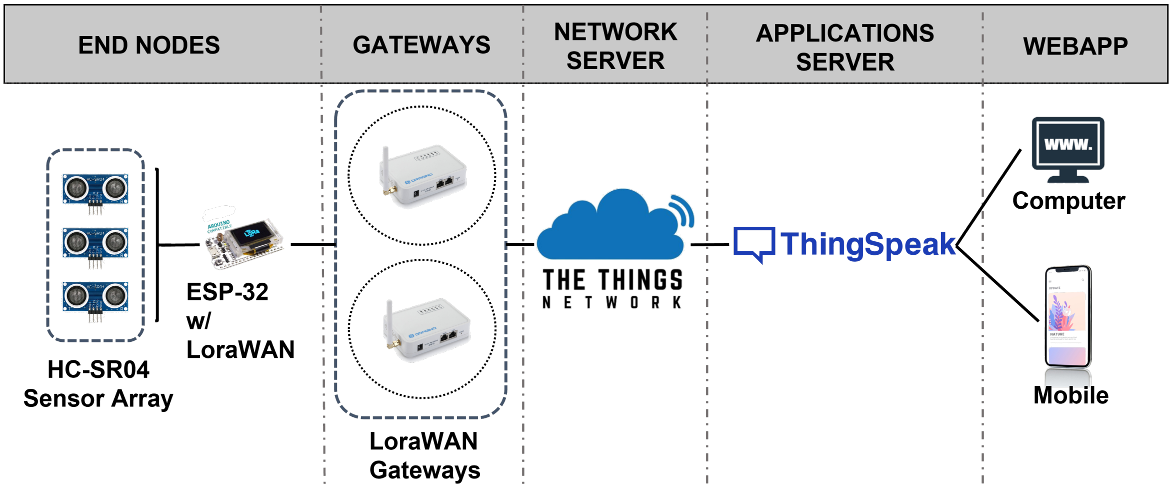

Fig. 2. Overall System Architecture.

III. System Architecture

Figure 2 depicts the overall system architecture. On the left side, it is possible to observe the end nodes, i.e. the LoRaWAN-enabled IoT Crowd Sensors, which in turn connects to the network server TTN (The Things Network) throughout the LoRaWAN Gateways (GW). These GWs communicate with the TTN (The Things Network) network server, and this, in turn, communicates with the Thingspeak Application Server where the data collected by the end nodes is stored and can be displayed through built-in and standardized dashboards provided by Thingspeak. LoRa is a radio frequency technology, developed for IoT devices, that allows communication over long distances (in urban areas 3-4 km range, and in rural areas up to 12 km or more), with minimal power consumption.

The IoT Crowd Sensor has been built with a SparkFun 1-Channel LoRa dev board, which has an onboard ESP32 WROOM module (with built-in Bluetooth and Wi-Fi) and an RFM95W LoRa module operating in the 868 MHz band. The device is composed of an array of three HC-SR04 ultrasonic sensors. Each array element will be responsible for detecting movement in the direction that each specific module is oriented. The ESP32 microcontroller is responsible for implementing the algorithm that controls the device operation, i.e. to estimate the number of people that is passing in a specific direction at a given place, such as hallways, courtyards, stairs, or pathways, and also to communicate, via LoRaWAN technology, with the TTN server, which is then integrated with Thingspeak through an HTTP RESTful API. The ThingSpeak platform was selected to store the data obtained by the IoT devices and to streamline the preparation of real-time dashboards. Thingspeak is an IoT analysis platform that allows the aggregation, visualization, and analysis of data streams, in a very simple way [9]. At the Frontend level, a responsive WebApp has been implemented which can be accessible by any device (i.e., a computer or a mobile device).

IV. IoT Crowd Sensor

The IoT Crowd Sensor has been implemented to evaluate two distinct geometries, cf. Figure 3. Initially, a geometry with only 2 sensors (Geometry A) disposed orthogonally (45° between each other) has been evaluated. Since the sensors have an approximately 30° angle radiation pattern [10], the measurement field did not match. However, a new central sensor has been added, and consequently both geometries have been evaluated. Several situations were analyzed with the 2 sensors and the 3 sensors, so that the positioning of the new sensor (Geometry B) would prove to be an added value in the low-cost context of the project. These analyzed situations go through a real simulation of the sensors in operation, that is, when one or more people pass in front of the sensor and the sensor always records the results for the comparative study of what the sensor was supposed to read with the real value read.

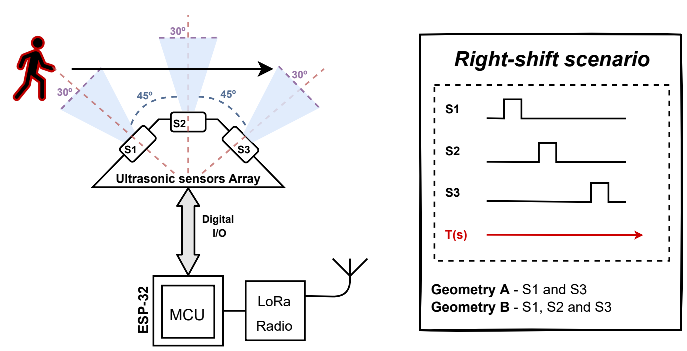

Fig. 3. IoT Crowd Sensor block diagram and operation principle.

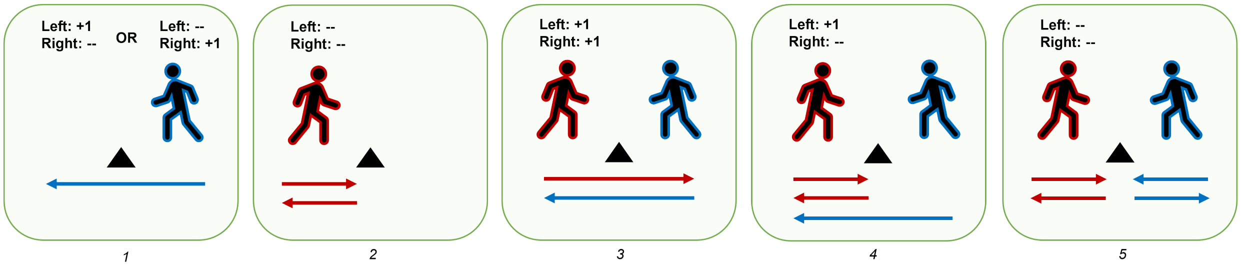

Fig. 4. Evaluation Scenarios.

A. Detection and counting algorithm

Before elaborating the crowd quantification algorithm, all the human detection and counting scenarios have been identified. Figure 4 illustrates all the scenarios that will be evaluated. Scenarios 1,2 and 3 have been evaluated for the 2 sensors geometry. For the 3 sensors geometry, all the scenarios have been evaluated. A more detailed analysis of the evaluation of both sensor geometries will be covered in the results section. It should be underlined that both geometries of prototypes were analyzed and tested, both with 2 sensors and also with the 3 ultrasonic sensors.

To this end, the state/flow diagram illustrated in Fig. 5 presents all the distinct scenarios considered in the implementation of the IoT Crowd Sensor with flow direction detection.

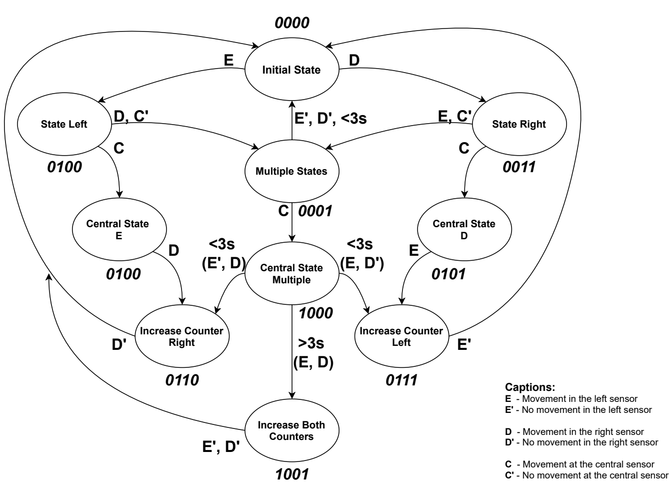

Fig. 5. IoT Crowd Sensor State/Flow Diagram.

B. Prototype

Figure 6 depicts the IoT Crowd sensor prototype. The prototype includes both 2 and 3 sensors geometries, which will be evaluated separately.

Figure 7 illustrates the WebApp Frontend which has been developed in PHP and HTML. The WebApp allows the

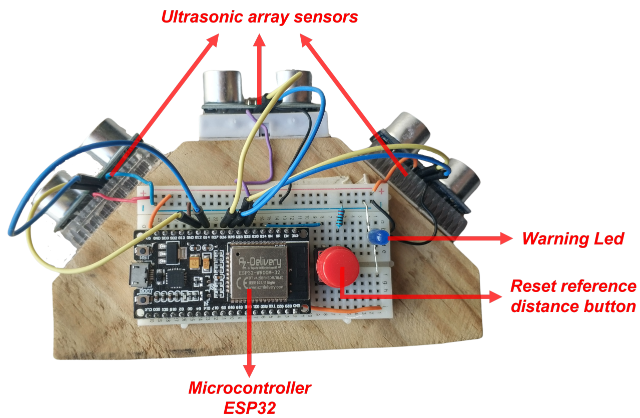

Fig. 6. IoT Crowd Sensor Prototype with US sensor array and microcontroller.

visualization of graphs with daily, weekly and monthly values, and also presents the flow direction estimation (left and right).

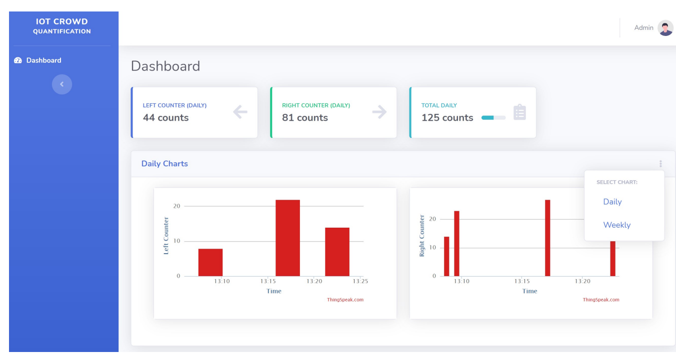

Fig. 7. WebApp Frontend.

V. Results

Results have been evaluated based on both geometries previously presented. In total, the IoT Crowd sensor is capable of detecting movement in two scenarios in which only one person moves and another three scenarios in which two people move, cf. Figure 4. The evaluation was performed based on scenarios presented in Figure 4. During the evaluation procedure, each scenario has been evaluated 40 times, with the prototype for both geometries, i.e., with a two-element array and a three-element array. Regarding the measurements and the accuracy of the IoT Crowd sensor, results have shown that the three-element array geometry proves to be the best approach, due to the fact that the results obtained proved to be more precise and accurate than the two-element array geometry. Table I depicts the results obtained during the experiments. Results show that there was a relevant improvement with the three-element geometry, especially in scenario 5 since with the two-element geometry it was not possible to obtain a valid detection.

TABLE I
MEASUREMENT RESULTS: GEOMETRY A VS. GEOMETRY B

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Geometry A (2 elements Sensor Array)	**100%**	**100%**	**40%**	**35%**	**0%**
Geometry B (3 elements Sensor Array)	**100%**	**100%**	**70%**	**60%**	**100%**

VI. Conclusions

This work proposed the design and evaluation of an IoT device for crowd quantification with flow direction estimation based on low-cost components. The proof of concept here presented consists of an IoT device with LoRa connectivity that has been designed to evaluate two distinct array geometries, with two and three ultrasonic sensor elements, respectively. Comparing the systems identified in the related works, we can focus on the advantages in which this project stands out. As a differentiating point, we use a Cloud IoT Platform to be able to store statistical data and later be visualized in any web application. The use of the LoraWan network is an advantage over the other means of communication for the systems identified because it allows a longer range with very low power consumption. In related work, the work of Karzan Raza and Wyra Monnet in [3], served as inspiration for this project. Their work also consisted in developing a system to detect a person's motion and direction using a linear array of ultrasonic sensors, and the system developed by the authors focused only on detecting a human body, whereas the system proposed in this project can identify and count scenarios up to 2 people. Based on the obtained results, the three-element array presents a considerably better accuracy. Moreover, the low-cost requirement has been met since each ultrasonic sensor (i.e. each array element) has a cost of approximately 3€. At the backend level, the Thingspeak allowed a simplified integration and ease graphing. In future work it is proposed to increment the number of ultrasonic sensors, since the increase from 2 to 3 sensors improved significantly, it would be important to analyze whether the implementation of another sensor would have a positive effect in obtaining results and thus achieve a more efficient sensor. At the software level, the development focused on the implementation of new technologies that would allow a new and practical approach in consulting the analyzed and developed values.

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