Design of a Smart Air Conditioning Controller Based on the Occupancy of a Building

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***Abstract*—This paper presents design of an efficient air conditioning control system that decides the number of air conditioning units to be operated based on the occupancy of a building. The objective of the research was to develop an automatic system using inexpensive electronic components and basic control methods in order to reduce electric power wastage in schools, colleges, offices, and homes. In this research, several experiments have been conducted to determine the optimum parameters for designing a cooling control set-up. The hardware implementation of the smart control system is presented and its performance is assessed. The proposed smart system was installed in building NJ10 at University of Jeddah, Jeddah, Saudi Arabia as a pilot project. As per the observations, energy consumption and cost can be reduced by a considerable amount, making the system efficient, when the proposed set-up is installed.**

***Index Terms*—Energy consumption, photoresistors, sensors, temperature control**

I. Introduction

Energy management is an important pillar for the economic growth of any country and therefore, finding new techniques to save energy and a balance between economic factors and energy efficiency is essential [1]. Home cooling or building cooling, is one of the most significant energy consumption activities, particularly, in countries with a hot climate. In Saudi Arabia, about 70% of the total electricity demand is spent on air conditioning of residential buildings [2]. With more than 1.5 million new homes estimated as the requirement for the expected population by the end of this decade, it is forecasted that domestic energy demand will be doubled [2].

Similar studies were conducted in several countries such as Australia, Brazil, Egypt, Latvia, Mexico, Nigeria, Spain and Zimbabwe to identify the correlation between multiple factors such as temperature, income, indoor comfort and air conditioning [3]-[11]. The research findings reveal how climatic changes and income of people impact electricity consumption. Researchers predict that use of air conditioning in all warm areas will be saturated within a few decades with peoples' desire on higher living standards. With such an exponential growth in the use of air conditioners, not only the energy consumption but also the electricity bills will be increased dramatically.

High energy consumption causes serious environmental problems. Air conditioners cause emissions and higher temperatures contributing to scenarios like greenhouse effect and global warming. In cities, some regions where most of the houses and businesses use air conditioners are being identified as urban heat zones that may severely affect weather [12]. Finite energy resources like coal, natural gas and oil will eventually run out. Therefore, invention of energy efficient solutions is a timely requirement [13]-[15].

There are some common problems associated with operation and control of air conditioners. Usually, air conditioning in public buildings exceeds the demand during weekdays, and some air conditioners are operated during weekends even with no demand. Air conditioning systems consume a higher amount of power due to the unavailability of inexpensive air conditioning control techniques and equipment. On the other hand, when the electric devices which have limited hours of consumption are operated continuously for a longer time, their lifetime reduces significantly.

Hence, identifying the importance of efficient power consumption for air conditioners, an inexpensive temperature control system is proposed in this paper. The proposed design counts the number of people inside the building and the required cooling load is calculated accordingly. The controller decides the number of operating cooling units to be operated based on that input.

Section II of this paper explains the energy-saving cooling systems and compares different temperature monitoring and controlling techniques. The methodology of developing the proposed system is presented in Section III. Step by step development of the experiment setup is explained in Section IV. In section V, the results of the research project are discussed. Finally, the conclusions and future developments are presented in section VI.

II. Energy-Saving Cooling Systems for Buildings

A. Existing Systems

During the cooling process, an air conditioner takes indoor air and cools it by passing through an evaporator coil before sending back to the building. When a thermostat is set to a certain temperature, the temperature of air inside the room is kept at the set point. The thermostat keeps checking and stops the compressor when the temperature reaches the desired level. The

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compressor is the most electricity consuming component of an air conditioner. In this process, the compressor will work for a longer period of time if the temperature is set to a lower value. When the thermostat reaches the desired temperature, the compressor stops and only the circulatory fan is operated. At this stage, the electricity consumption is reduced to the power requirement of the running fan. The compressor will restart when the thermostat detects that the temperature exceeds the desired level. An increase of one degree Celsius in the set temperature can save 3-5% of the consumption [16]-[17].

There is an increasing demand for energy-saving techniques and devices among the suppliers. There are some expensive devices in the market, in the brand names of Ecobee, Lyric, Lux, and Nest. These devices use smart thermostats that can be used in home automation systems to control heating and air cooling. They allow users to adjust temperature settings over internet-connected devices, such as a laptop or a smartphone [18]. Such a system can perform programing itself by learning the user behavior patterns and desired temperatures for specific days and times during the week. Then it defines a schedule for the heating, ventilation, and air conditioning (HVAC). Table I presents the specifications of two such products.

Ecobee is an intelligent scheduling and presence detection system that automatically detects whether the user has adjusted their HVAC accordingly. It uses remote sensors to measure temperature and presence of the user in a building or a home. It then controls the temperature in the building based on the user's location or the average temperature of the central unit and the remote sensor. It can be used to maintain hot or cold spots in the home, even if the thermostat is installed in a single location of the house that has a temperature different from the main living areas [19], [20].

The major drawback of these devices is that they can only detect the presence of the user when their smartphone is connected to the internet. In recent years, there has been an increase in the demand for home automation or building automation. The most widely applied systems are the cooling and heating systems with multiple temperature control systems.

There are advanced temperature control systems for heating and cooling system invented and patented, but there is a limitation to run these systems because it must be connected to a computer whenever the system needs to be reprogramed [21]. Such systems consist of a thermal sensor operates on the difference between the set temperature and room temperature. However, even when there is no one presents inside the room, cooing system works causing energy wastage. Numerous applications such as temperature monitoring in power transmissions, server room temperature measurement using Bluetooth embedded systems, electric cable interference and control systems for communication rooms use wireless temperature monitoring systems [22]-[24]. Temperature sensors and Zigbee based temperature measurement systems are expensive and need re-programming experts [25]-[26].

B. Heat Load Measurements

Indoor temperature depends on numerous sources, such as occupants, computers, copiers, machinery, and lighting. Warm air from outside can also enter through opened doors, windows or holes. However, the most significant source of heat is solar radiation from the sun. The temperature rise due to all of these heat sources is defined as the heat gain or heat load of a building and is expressed either in British Thermal Units (BTU) or kilowatts (kW). For an air conditioner to cool a room or a building, its output must be higher than the heat gain. Therefore, it is essential to do a heat load calculation before purchasing an air conditioner in order to ensure its output is sufficient for the intended application [17].

Air conditioners are rated by the number of BTU of heat they can remove per hour and measured in refrigeration tons. A ton is equal to 12,000 BTU/hr or 0.293 Wh. The heat gain or heat loss through a building depends on numerous factors such as the difference between the temperature inside and outside of the building, the type of construction, insulation in the roof and walls and air leakage through doors and windows. Further, number of people in the building and equipment located within the premises also influence the heat gain. For an example, if a comparison is made between a bedroom and a kitchen, the difference would be considerable. Heat gain depends on the type, quantity, and quality of lighting used inside the room too. Therefore, the air conditioner's efficiency, performance, durability, and cost depend on these factors [17].

TABLE I: PRODUCT COMPARISON

Product Item	Nest	Ecobee
Control Method	Controls the temperature	Controls the temperature
Detection Method	Thermostat	Thermostat
Data Requirement	The temperature in the building and people present	The temperature in the building and people present
Application Fields	Houses	Houses
Energy Saving	10-12%	23%
Set-up	Easy	Complicated
User Interface	Yes	Yes
Smart System	Quickly understands the schedule and get adjusted	Uses Smart scheduling
Cost	Around $250 (+$40 for an additional sensor)	Around $200 (+$40 for each room temperature sensor)

There are different methods available to calculate the heat load with a diverse range of accuracy. If a high accuracy is required, precise calculations need to be done. There is a simple equation to calculate the heat load that has an acceptable accuracy. It can be used to estimate the heat load in a building, and for each person that enters the building, a heat load of 500 BTU is added (1). The output of the cooling load from the air conditioners must be higher than the heat load in order to cool the building.

$$\text{Heat load} = hwlc \tag{1}$$

where *h* is the height of the building in meters, *w* is the width of the building corridors in meters, *l* is the length of the building corridors in meters, and *C* is a constant with a value of 141.

III. Methodology

The block diagram of the proposed inexpensive system is shown in Fig. 1. In the hardware implementation of the design, an open-source microcontroller (Arduino) was used for the simplicity of programming and reliability of the performance [27]. The circuit board was built with unsoldered components to make the experiments easy to handle and to allow the quick identification of issues at the prototype stage. Several types of suitable sensors required to implement the control system were studied and their details are summarized in Table II.

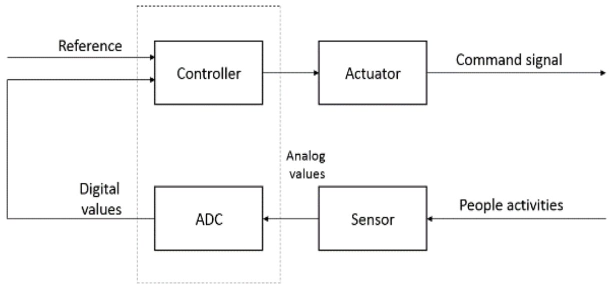

Fig. 1. Block diagram of the system.

TABLE II: Sensor Comparison

Product	Advantages	Disadvantages	Cost
PIR	Range is about 6 m. Can identify a human body. Does not need Tx.	It is affected by external heat sources. Needs adjustment time—delays between object passes.	Moderate
Ultrasonic	Detects unseen objects. Is not affected by dust. It can detect complex shapes.	Interference in array design . Range about 4m. Gives false readings for soft objects.	Moderate
Microwave	Long Range up to 15m. High Frequency (10.525 GHz). Direction determining.	It detects non-humans. High power consumption.	Expensive
Photo-resistors	Easy to handle (as a resistor). Long Range (Depends on the Laser source).	Needs separated Tx. Gives false reading if the area is crowded.	Inexpensive
Infrared	Transceiver needed. Low power consumption (3 -5 mA).	Very short-range (300 mm). Radiation could be absorbed, giving a false reading.	Inexpensive
3D Camera	More robust. Better quality. Better functionality.	Low frame rate. Not accurate during motion. Sensitive to optical interference from the environment.	Expensive

The control system consists of three electronic circuits; a sensor circuit, an actuator circuit, and a primary controller circuit. The major components used to build the system are Arduino, Red Dot Laser Diode (5mW 650nm), photoresistor, NRF24L01 transceiver module, Arduino LCD and I2C Serial Interface adapter module [28]. In the sensor circuit, the LDRs were connected to analog pins (ADC inputs) for the detection of objects or people. An 880 nm infrared emitter was used in the actuator circuit. An infrared LED was configured to increase or decrease the number of operating air-conditioners by using the same frequency used in the remote control unit. The primary controller circuit consists of three Arduino boards connected via serial ports. It facilitates the receiver to send received data to the SD writer to record the detection and to the transmitter to send a control signal to the actuator.

A pair of laser was used with a pair of photoresistors as sensors that are placed 1.6m above the ground. The sensors were connected to the microcontroller system using wireless network modules. The central controller is connected via a serial port to the other modules to record the detections and to give commands to the actuator, which provides a control signal to the air conditioners. The Photoresistor unit is connected with a voltage divider configuration. It senses objects based on variations in laser light that is placed in line-of-sight with the photoresistor. The controller senses the value of analog voltage via a built-in analog to digital converter (ADC).

When an object passes the photoresistor and breaks the laser beam, the voltage varies. Then the pre-set value programmed in the controller is compared to detect whether the number of people falls within the acceptable range to be served by the number of air conditioners in operation. Accordingly, the number of operating air-conditioners is increased or decreased by sending a command signal to the air-conditioner controller.

IV. Experimental Setup and Results

After constructing and programming both the primary controller circuit and the object detection sensor system, they were integrated and tested for the efficiency of the system. Multiple tests were done to assess the system performance and to determine the effectiveness of the designed system. Different scenarios such as bidirectional motion, crowded motion, and the effect of sunlight on photoresistor readings were covered. Communications between the central controller and the object detection sensors were also tested and the decision making capability of the controller was checked. The experimental set-up was installed at the building NJ10 of University of Jeddah. The objective of the experimental set-up was to test the detection performance and to use this configuration to implement a real-time system after confirming proper operation.

Several experimental iterations were performed by changing design parameters, as explained below. Error calculations [29] for sensor readings for each period are given by (2):

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$$e = e_{tot}/N_e \quad (2)$$

where e_{tot} is the total percentage of errors and N_e is the number of errors.

A. Crossing Detection Experiment (Experiment #1)

In this experiment, distance between the photo-resistors was kept as 30mm. The height above the ground was 0.7m. This configuration gave inaccurate readings because it detected the legs of the passing persons and sometimes provided a reading of two separate entries per person [30]-[31]. Further, standing in front of the lasers disturbs the sensor to take readings [32]. Based on the results, it was decided to install a proper housing for the laser setup to improve the precision of detection [33], [34]. Table III summarizes the results of the first experiment.

B. Dimension Adjustment Experiment (Experiment #2)

Stands were added to both the laser and photoresistor to increase their height above the ground [35], [36]. It was observed that the sensor was still inaccurate because the separation between the photoresistors was insufficient. If a person that passed the detector was carrying an object (like a glass, cup, or water bottle), then the sensor counted them as two people (Fig. 2.). Table IV summarizes the results of the second experiment.

TABLE III: READINGS OF EXPERIMENT #1

Time	Experimental number of readings	Actual number of people	Error
12:30	14	14	45.1%
13:03	2	9	
13:15	4	7	
13:30	6	3	
13:49	5	1	

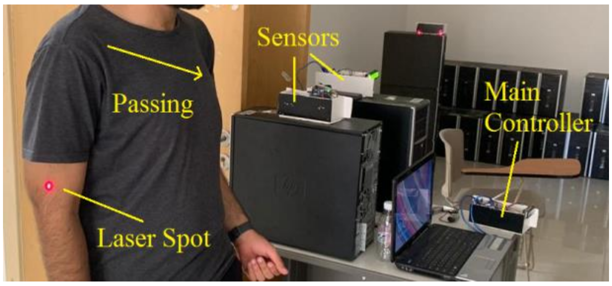

Fig. 2. Experimental set-up which shows detection of a person enters the building.

TABLE IV: READINGS OF EXPERIMENT #2

Time	Experimental number of readings	Actual number of people	Error
9:30	18	12	43.0%
9:47	15	21	
9:57	14	9	
10:03	4	13	
10:18	7	9	

TABLE V: READINGS OF EXPERIMENT #3

Time	Experimental number of readings	Actual number of people	Error
10:07	18	18	16.6%
10:15	21	21	
10:19	20	16	
10:24	12	17	
10:32	12	17	

TABLE VI: READINGS OF EXPERIMENT #4

Time	Experimental number of readings	Actual number of people	Error
9:30	11	11	14.1%
9:47	8	8	
9:57	5	7	
10:03	10	11	
10:18	4	3	

C. Separation Enhancement Experiment (Experiment #3)

The separation between the photoresistors used in experiment #2 was 30 mm. The separation in this experiment was increased to 150 mm after several trials, which increased the accuracy of the readings. Unlike in the previous test, a person carrying an object was correctly counted as a single person. However, after a certain period of time, the laser started radiating with a low beam concentration due to drained batteries [37]. It impacts the accuracy of the photoresistor readings [38]. As a solution, the batteries were replaced by a power bank that works over an extended period. Table V summarizes the results of the third experiment.

D. Head Detection Experiment (Experiment #4)

In this experiment, the height was increased to 1600 mm while keeping the same separation giving an increased accuracy of the readings. This improvement was happened as only one object was detected per person at the height of head or neck [39], [40]. Even if a person was carrying a bag or a cup, this would not affect the readings. Further, a liquid crystal screen was added to monitor the readings and to indicate whether the system working or not. Table VI shows the improved results.

E. Overall System Test (Experiment #5)

The previous experiments were done to test the accuracy of detection perform by the sensors and to improve the system performance gradually based on the results. The observations were hand-written and records were kept on paper. In this experiment, an SD card module was added with wireless communication facilities to collect a higher number of samples quickly. A real-time clock module was added to record the detection time [41]. Results of the fifth experiment are illustrated in Fig. 3. In the detection plot, “1” is used to represent a person enters the hall and “0” to represent a person leaves.

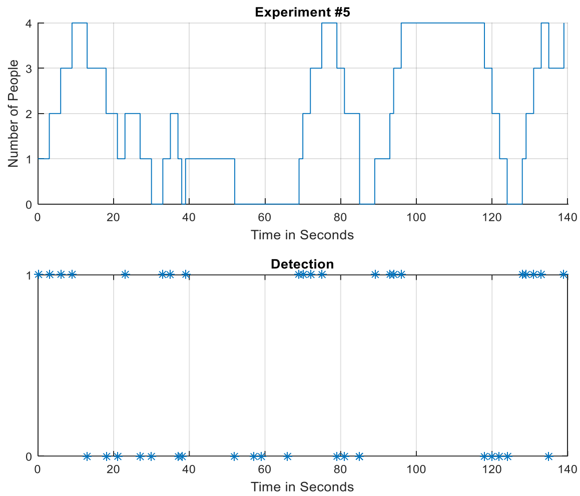

Fig. 3. Performance of the overall system reported in experiment #5

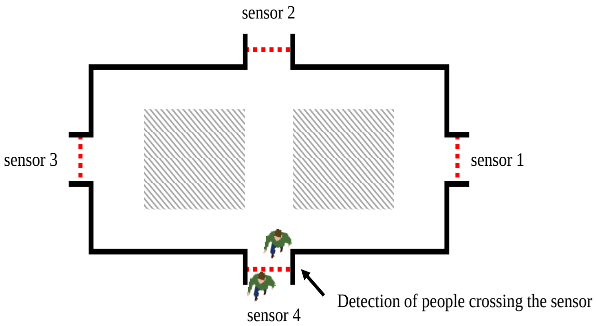

Fig. 4. Layout of building NJ10

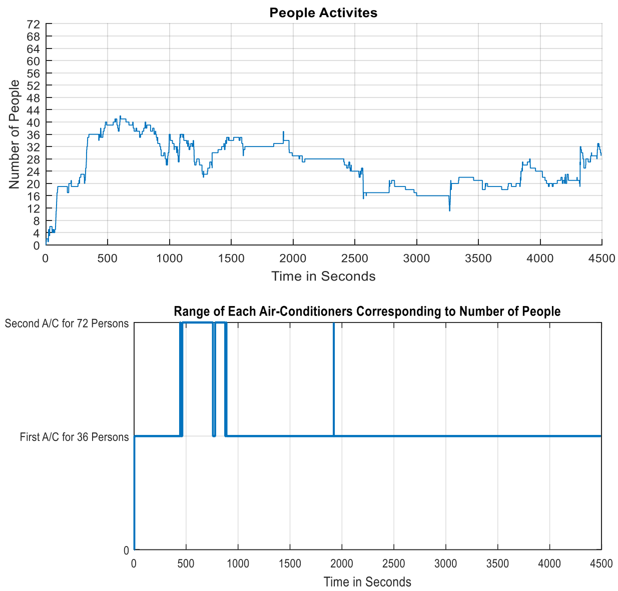

Fig. 5. Implementation results: Case 1.

F. Real Case Scenario with Heat Load Measurements (Experiment #6)

Experiment #6 was conducted to test the overall system performance by doing a pilot project. The layout of the building used for the pilot project is illustrated in Fig. 4. Cooling load calculations were done for the building and the algorithms are written in MATLAB to sketch the energy level. Fig. 5 shows the results of the experimental set-up implemented at the entrance of a building.

The required BTU for cooling was calculated by applying values to (1). There are eight air conditioners in this building, each delivering 18000 BTU/h. As per the calculations, six air conditioners are sufficient to cool the building ($6\times18000 = 108000$). An additional 500 BTU is added for each person that enters the building. Once the BTU value passes 110000 BTU, then an additional air conditioner starts its operation.

Implementation results of two test cases conducted at the pilot project are shown in Fig. 5 and Fig. 6. Each pulse of the energy level represents starting the operation of an additional air conditioner. It was observed that the system turns off an air conditioner with a slight delay. It is clearly shown in Fig. 6 that when a person enters the building, one air conditioner starts to operate. It remains unchanged until the total number of people exceeds 36. If the total number of people exceeds 36, another air conditioner starts to operate.

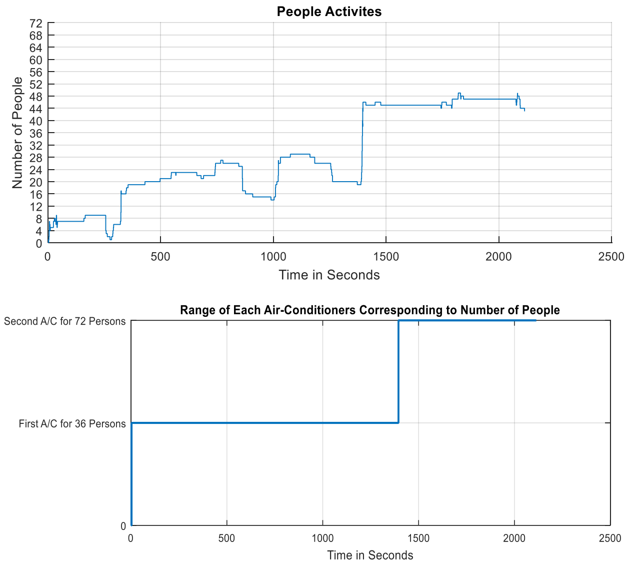

Fig. 6. Implementation results: Case 2.

V. DISCUSSION

The proposed air conditioning control system was designed with gradual improvements as explained in section IV. The first four experiments were done to assess the performance of the object detection sensor unit and to optimize the placement of the set-up. As per the results of the Experiment #1 the lasers should not be placed very close to the ground level. In experiment #2, the set-up was placed at waist level. Though the accuracy of the readings improved, avenues for further improvement of the accuracy were identified. In experiment #3, separation between the photoresistors was increased and the accuracy of the readings could be improved further. Further, use of a power bank expanded the operating period of the sensor. In experiment #4, system was improved to monitor the readings with an accuracy of more than 85% in identifying the number of people inside the building. The overall performance of the system was assessed in experiment #5 with automatic collection of samples.

Finally, a pilot project was conducted after doing the heat load calculations for a selected building and the performance of the overall smart system was observed (experiment #6). The energy-saving achievements of the proposed air conditioning control system are presented in Table VII. As per the results, more than 92MWh can be saved in the selected building per year. It will reduce the electricity bill by $3840. In comparison to the expenses made for the proposed design, the saving is a huge amount.

TABLE VII: RESULTS OF THE PILOT PROJECT

Performance Parameter	After installing the proposed smart system in the building	Before installing the proposed smart system in the building
No. of operating units	6 - 8 Units	8 Units
Heat load	108,000 BTU/hr	144,000 BTU/hr
Heat load	31.644 kWh	42.192 kWh
Energy consumption per year	277,201 kWh	369,602 kWh
Cost	$13,900.00	$17,740.00

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VI. Conclusions and Future Developments

In this paper, an efficient and low cost air conditioning control system is presented. It determines the occupancy of the building and automatically adjusts the required number of air conditioning units. Therefore, a minimum number of air conditioners are in operation at any time, which ultimately reduces the power consumption and electricity bill. Even if everybody will leave the building without switching off the air conditioners accidently, they will be switched off automatically, as this smart system identifies the unavailability of people.

The system was developed using inexpensive components and successfully implemented to be integrated in existing building management systems. It was evident that the proposed smart control system can deliver a reduction in energy bill by around 22%. It may be reduced further depending on the structure of the building. The proposed system saves around 92,400 kWh annually, while increasing the life cycle of cooling devices. The developed control unit can be installed in any building, by simply customizing only the software implementation.

Authors have identified some more developments that can be applied to improve the work further in the future. More intelligent motion detectors such as 3D cameras can be used to confirm whether the detected objects are human or non-human. Height adjustments can be made with an array of sensors to detect wheelchair users, adults shorter than 1600 mm, or young children. Continuous detection can be used to determine the activity levels of the people inside the building. The systems can be modified to perform multiple tasks such as controlling both the air conditioners and the lighting. Engineering designing in SolidWorks, Ansys or AutoCAD can be done to design bespoke systems based on customer requirements. In the case of central air conditioning systems, control of temperature using variable air-flow valves installed in the air conditioner vents instead of increasing or decreasing the number of air conditioners can be performed. A software application can be developed to interface a wireless monitoring platform with the control system. A continuous monitoring mechanism can be implemented to detect the connections and proper functioning of sensors. A back up configuration and data scheduling can be done as a safety measure in case of an emergency shut down or power failure.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Dr. Anas M. Hashmi supervised this work and contributed in shaping the project requirements and focus. Other authors worked interchangeably in developing the electronic circuits, system testing and troubleshooting.

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