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Development and scaled-up simulation of an automated electrical energy management system for passageway illumination

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Abstract: Buildings account for much of the world's energy consumption; thus, it is important to develop ways, not just to harness more of the energy in the universe, but also to make system of devices in buildings more energy-efficient. Occupancy-based illumination is an emerging trend in energy management, but research in this field has mostly been focused on illumination of rooms and work-spaces in building interiors. To the best of the authors' knowledge, there is virtually no literature on the energy optimisation of depersonalised spaces such as passageways. This paper explores the development and evaluation of a controller-based model for illumination of passageways in buildings, where relatively-large number of depersonalized luminaires are usually found and automation might prove especially beneficial. After development, testing and scaled-up simulations, results show that occupancy-based illumination of exterior corridors and semi-covered passages in buildings is feasible, economical, has significant energy savings, and is worthy of consideration for modern buildings.

Keywords: automated illumination; energy management; microcontroller; occupancy; PIR sensor.

1 Introduction

Significant amounts of energy are wasted in buildings [1, 2]. Occupancy-based energy management involves regulating the energy usage in physical spaces, usually in buildings and other manned structures, based on parameters such as the presence, absence, number, position and habits of temporary and permanent occupants of such spaces. Since most of the energy-using systems in buildings are designed for purposes relating to the comfort and productivity of the occupants, the required operation of such systems and their components varies with the occupancy state of such buildings, as defined by such parameters as the presence, absence, positions, number, and, even possibly, identity and health status of building occupants.

Occupancy-based energy management takes building automation further by not only reducing drudgery, but also energy wastage [3, 4]. Lighting accounts for a major proportion of energy wastage in residential and commercial buildings [5]. There have been occupancy-based illumination schemes implemented in interior rooms in test-bed office buildings, which have shown promising results [6, 7]. Unfortunately, the blocks of lighting fixtures in external corridors of buildings are a major source of energy wastage due to being left switched on when not needed (when the part of the corridor lit by such a fixture is unoccupied or otherwise adequately illuminated by natural light). This problem is addressed in this work, with an occupancy-based model of a system for energy-efficient passageway illumination.

Various methods and sensor types have been developed for occupancy-state observation in buildings, implemented in applications such as intruder-alert and access-control systems, building automation systems, activity-logging systems, among others. The choice of methods and sensors depends on several factors such as the purpose of occupancy sensing, the environment, and the parameters of interest, and the economics and financial specifics of the project.

The use of cameras for occupancy-sensing is very useful in security applications, with the numerous advantages that come with recording visual imagery and the potential for features such as biometric identification [8].

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However, with existing technology, camera-based systems are expensive, complex and are unable to cope with sudden and rapid changes in the occupancy state of a space such as a passageway.

Carbon dioxide sensors are one of the most modern ways of occupancy sensing, but, in addition to their cost, they have slow response times, and are more suited for enclosed, climate-controlled spaces where humans are the only significant source of carbon dioxide [9, 10]. These reasons make CO₂ sensors as an occupancy-sensing method unsuitable in external passageways.

The use of user-borne wirelessly-communicating devices such as wristwatches and smartphones in systems to track the occupancy state of buildings has been researched [11, 12]. Systems of this kind usually have the added benefit of integrating identity information of occupants when necessary, but this is both unnecessary and difficult to achieve in a public space with unrestricted access to people such as an external passageway in a building [13]. Also, since it is really devices being tracked and not humans, and since wireless signals can pass through walls, such systems are prone to false positives [14, 15].

More economically, occupancy can be sensed by the use of ultrasonic sensors that can be either active or passive [16]. Passive ultrasonic sensors usage is still in the experimental stages, with not much recent literature on it [17].

Active ultrasonic sensors are more commonly used, cheaper and more easily used. Primarily rangefinders, they are easily adapted to detect presence [7]. However, they have the major drawback of being unable to distinguish between humans and inanimate objects and they can be confused by Heating and Ventilation systems. They usually have narrow fields of view, are active sensors that consume energy, and with most commercially-available models, their sensitivity was found to be difficult or impossible to control.

For the purpose of this study, Pyroelectric Infrared (PIR) Sensors were used. These are sensors that detect infrared radiation emanating from objects in their field of view. They are passive sensors, and are also known as Passive Infrared Sensors. A PIR sensor has transducers made of pyroelectric semiconductor materials that make up one or more sensing elements that convert impinging infrared energy into electrical energy. Most practical usages and commercially available forms apply a Fresnel lens to improve the field of view of the sensor. The sensing element itself produces an analogue output [18, 19]. However, direct usage of the analogue outputs in occupancy detection is complex, only occasionally managed in laboratory settings, and still in its experimental stages [20].

Commercially-available modules are available with built in signal-conditioning of the raw analogue outputs of

the sensing elements, to provide signals usable with digital systems, and the workings of these modules depend largely on the integrated electronics added by the manufacturers. The more-sophisticated PIR sensors have been used for human identification and tracking [21]. Most commercially-available PIR sensors have fewer sensing elements and are mainly used as motion sensors, but are found to be applicable to sensing human detection in passageways, where occupants are mostly in motion.

In this work, a model for automated energy management system for passageway illumination was developed, a microcontroller-based model was built and tested with the selected components on a reduced scale and tested for qualitative performance investigation and simulated on a realistic scale using MATLAB for quantitative performance investigation. The work describes the system hardware and software used to achieve the objectives, as well as the process and results of the simulation and performance investigation.

Along the way, the work describes a method used to directly connect an analogue Light Dependent Resistor (LDR) based light-sensing circuit with a controller digital input pin, without using inbuilt or external analogue-to-digital conversion.

2 Materials and methods

2.1 Materials

ATMega328P microcontroller with Arduino bootloader was used in this study. It was programmed in embedded C++ language on a Windows 10 machine. The lighting fixtures used were 40 W incandescent lights, the PIR sensors were HC-SR501 model with double trimpot, purchased along with all other components used, from Hub360 Electronics and Melotex Electronics in Nigeria.

Data visualisations were done in MATLAB and Excel. Appropriately-sized copper cables were used for the AC power cables, while the signal wires were individual strands of Twisted Pair (TP) cable. The code was initially tested using an Arduino development board, with a low-voltage DC model of the system built on breadboard.

The power and control electronics were assembled by hand-soldering on stripboard also using PCB screw terminals and terminal block connectors, and placed in plastic housing, with slots for exposure of the LDR and the Potentiometer adjustment. The PIR sensors and lights in the model were assembled on a reduced physical scale and supported on a plywood platform for testing. The model system was protected with a fuse in the live arm of the mains supply as well.

2.2 Block diagram of developed model

Figure 1 shows the block diagram of the system as designed and built. It shows the subsystems' interrelationship with each other. There is a power supply circuit to take AC mains power and distribute into the

parts of the system at the appropriate voltage levels. There is the array of PIR sensors, a light-quantising circuit to measure the ambient lighting, an override mechanism to allow the system operate in traditional “always ON” mode, a microcontroller and its peripheral external components, a power amplification and switching circuit to relay the microcontroller commands to the luminaires, and there are the luminaires themselves.

2.3 Circuit diagram of developed model

The circuit diagram of the system is shown in Figure 2. The transformer TR₁, bridge rectifier BR₁, smoothing capacitor C₁, the LM7812 and LM7805 voltage regulator ICs labelled IC₃ and IC₄ respectively, with datasheet-recommended capacitors C₂, C₃, C₄, and C₅ make up the voltage rectification and regulation system to distribute the power to controller IC₁ and connected sensing components at 5 V, and to the current driver and switching components at 12 V.

A potentiometer, POT₁ and LDR, labelled LDR₁, are connected in series to form a potential divider and the light sensing network, resistor R₃ and light emitting diode, LED₁ form a visual “power on-off” indicator for the system. An ATmega328P microcontroller, labelled IC₂, takes digital input from three PIR sensors labelled “PIR 1” through “PIR 3”, the light sensing network, and a toggle switch (with a pull down resistor R₂), which serves as the override mechanism. Part of the microcontroller code ensures that, while the toggle switch is switched on, all the lights are switched on regardless of passageway conditions. This is suitable for troubleshooting the system or where the traditional “always ON” operation is desired.

Resistor R₁, capacitors C₆ and C₇, and a 16 MHz crystal oscillator labelled XTAL₁, are datasheet-specified peripherals of the ATmega328P microcontroller. A ULN 2003 transistor array IC, labelled IC₁, serves as a power amplifier and relay driver with in-built flyback diodes, switching the relays RL₁ through RL₄ at 12 V based on the digital outputs of the controller at 5 V logic level. The relays themselves each switch lights L₁ to L₄ at 230 V mains level, based on the microcontroller output sent through the relay driver.

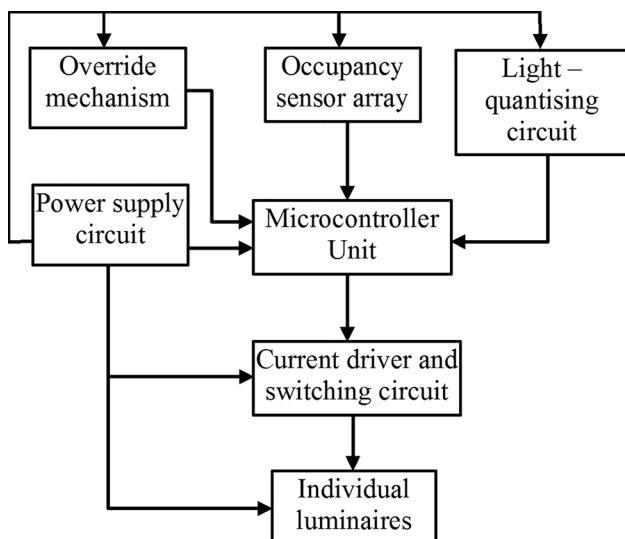


Figure 1: Block diagram of occupancy-based energy management system.

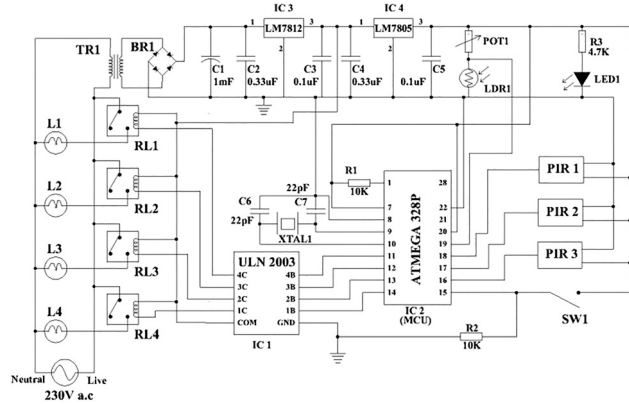


Figure 2: Circuit diagram of occupancy-based energy management system.

2.4 Daylight-sensing and quantising circuit

The system is designed such that, while the ambient/natural lighting levels of the exposed passageway are deemed sufficient by the microcontroller, all lights are switched off regardless of occupancy states. This is accomplished by means of the voltage divider circuit shown in Figure 3, which comprises of a Light-dependent resistor (LDR) and a potentiometer.

In most light-measuring microcontroller applications, a fixed resistor is connected in series with an LDR and the voltage across the LDR is either fed into an analogue-to-digital (A/D) converter before feeding into the microcontroller or fed to an A/D-enabled input of the microcontroller, necessitating the inclusion in the code of sampling, quantisation and arithmetic comparator operations on the raw voltage, for the controller to decide on whether the ambient brightness is sufficient or not. The lighting-level threshold is also usually only adjustable by changing the microcontroller code.

The method used in this work eliminates the need for the quantisation and comparator operations mentioned in the last paragraph, which also makes for reduced memory requirements and faster code, and the illumination threshold is tunable ‘by user’s feel’ by using a potentiometer in place of a fixed resistor.

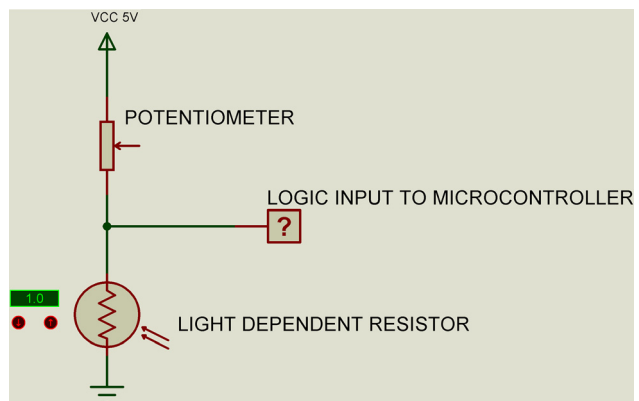


Figure 3: Daylight-sensing and quantising circuit.

This involves feeding the output of the voltage divider directly to the digital input pin of the microcontroller, and by taking care of relevant parameters, we take advantage of the fact that the microcontroller sees the analogue input as a two-state input, thereby self-digitising, self-quantising, and self-comparing the input.

For microcontrollers such as the ATmega328P being powered at a fixed voltage, it was found during this project that the voltage at which a smoothly-varying input changes from a detected logic high to a detected logic low and vice-versa is constant for that controller. This voltage, labelled V_h , is such that when the voltage at the microcontroller digital input (in this case the output of the voltage divider - the voltage across the LDR) is higher than or equal to V_h , the microcontroller detects logic high, otherwise, a low logic is detected.

Thus, in the LDR-potentiometer network in Figure 3, when the light levels change, the voltage at the microcontroller input change in the opposite direction, with the exact mathematical relationship being dependent on the amount of potentiometer resistance acting in the circuit. Thus, by manipulating the potentiometer resistance, the circuit is tuned such that at the desired light level threshold, V_h is the voltage dropped across the LDR. This means that, above the desired light threshold, the LDR voltage will be less than V_h , and the microcontroller detects a low logic, which, according to the controller code, is directly interpreted to mean that the environment is not too dark yet, while, below the lighting threshold, the microcontroller detects a high, which tells the controller that the lights are needed by anybody passing through the passageway.

Thus, by use of an LDR-potentiometer voltage divider as shown, the microcontroller receives the output of the light-sensing circuit as only a single input bit and directly stores and manipulates it as a Boolean variable, reducing required hardware resources and making for smaller and faster code, with no need for A/D conversion, comparator operations, or quantisation.

2.5 Microcontroller stage

In the small-scale model, five digital I/O pins of the ATmega328P microcontroller are configured as inputs. One I/O pin is the input from the daylight-sensing portion of the circuit, another I/O pin is for the override switch and three more I/O pins are connected to the three PIR sensors.

Four more digital I/O pins are each configured as output pins for controlling each lighting fixture. The ATmega328P microcontroller has analogue-enabled inputs. However, the use of these analog pins is deliberately avoided in this design to demonstrate the advantage of the designed daylight-sensing circuit, by eliminating the need for A/D conversion hardware components if the design is to be mass-produced or scaled-up using custom-designed IC. The need for A/D conversion arithmetic operations in the control program of the embedded controller is also eliminated.

The condensed flowchart for the microcontroller code is shown in Figure 4, due to the fact that there are three different PIR sensors in a staggered arrangement with four different lighting fixtures as shown in Figure 5, in which lights and PIR sensors are labelled with numbers prefixed by L and S respectively.

The ATmega328P microcontroller makes use of Arduino-based source code which consists of library and variable declarations, a setup function that executes whenever the chip is powered on or reset, and a loop function that executes repeatedly after a single execution of the setup function.

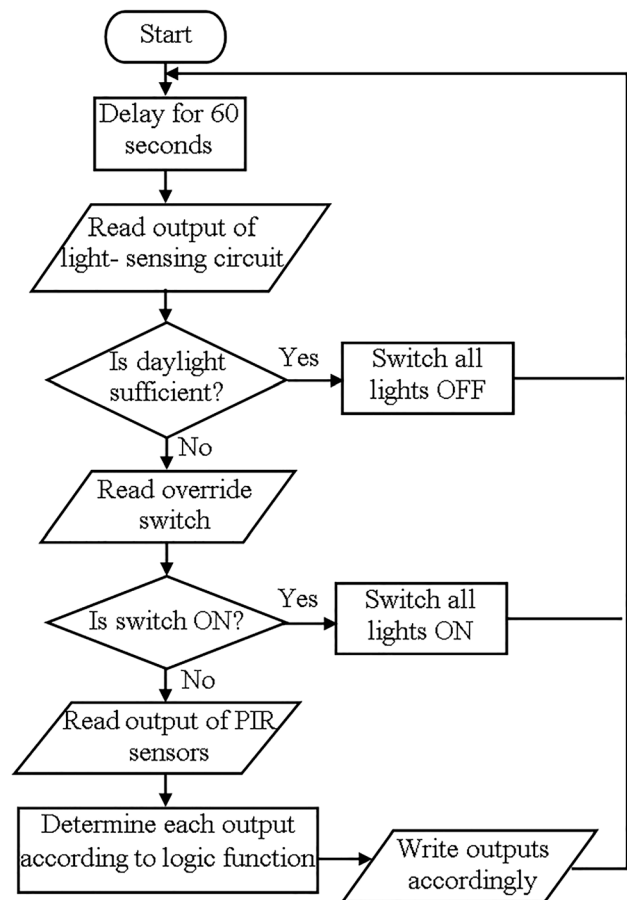


Figure 4: Simplified flowchart of microcontroller code.

When the system as, implemented by authors, is first connected to the power supply, the control program specifies an “ALL ON” configuration for all the connected lighting fixtures in the passageway for a few seconds. There are three reasons for this feature. The first reason is to allow for thermal stabilisation of the PIR sensors. The second reason is to provide a quick visual test of all connected luminaires upon initialisation of the system. The third reason is to provide illumination immediately power is restored after a blackout.

After the waiting period of 1 min, the loop function implements the code that checks whether the ambient lighting is sufficient or not: if it is, the lights are all kept off, if it is not, the microcontroller checks the PIR sensors and switches on the lights in the vicinity of any of the PIR sensors that detects someone in its field of view, until a desirable time (in this case, 6 s), after the PIR sensor output goes from high to low (to compensate for the cooldown period of the sensor). The loop function executes indefinitely or until thousands of times a second but the code is written to maintain integrity in timing of actions across multiple

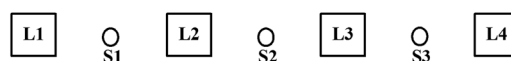


Figure 5: Spatial arrangement of lighting fixtures and sensors.

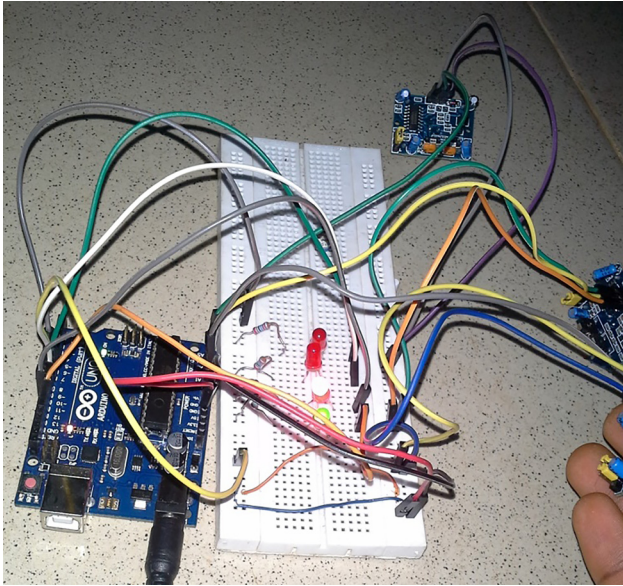


Figure 6: Testing of the code on microcontroller.

loops and time variable overflows. Figure 6 shows the preliminary testing of the code on an Arduino board.

2.6 HC-SR501 PIR sensors

Three PIR sensors are used, labelled PIR 1, PIR 2, and PIR 3. They are HC-SR501 sensors with their outputs being fed to microcontroller input pins. The HC-SR501 is a three terminal device with the other two terminals apart from the output being 5 V rail and ground terminals. The sensor can be configured in a one-shot mode or retrigger mode, but the latter is used in this study. The high output can be either 3.3 V or 5 V depending on the manufacturer but both levels are suitable for use with the ATmega328P. For the newer models, the sensitivity and cycle-time are both adjustable by means of attached trim-pots. It is a passive sensor, and the current drawn, when triggered, was found to be about 1 mA at 5 V, with a specification of 50 μ A quiescent current. This equates to a peak power consumption of only 5 mW when triggered and only 250 μ W when not triggered.

The HC-SR501 is a relatively simple and cheap sensor. It incorporates a Fresnel lens to cover a wide area and balance out the sensitivity in its field of view. It requires a warm up period, which mandated a 1-min waiting period to be built into our code. It also has a cooldown period of 2–4 s, after the end of each triggering period, that introduced a degree of complexity and flexibility into the coding requirements which solves the problems this could have caused. This being the major limitation, the sensor is still a useful, simple, cheap and versatile device as demonstrated by its successful incorporation into this project. The Fresnel lens (not shown) is on the other side of the sensor.

The PIR sensors are each positioned to cover a section of the passageway to measure the occupancy state of the walkway by checking for sizable and mobile infrared radiation sources. Figure 7 shows the partially assembled system electronics excluding sensors and luminaires while Figure 8 shows the luminaires and sensors.

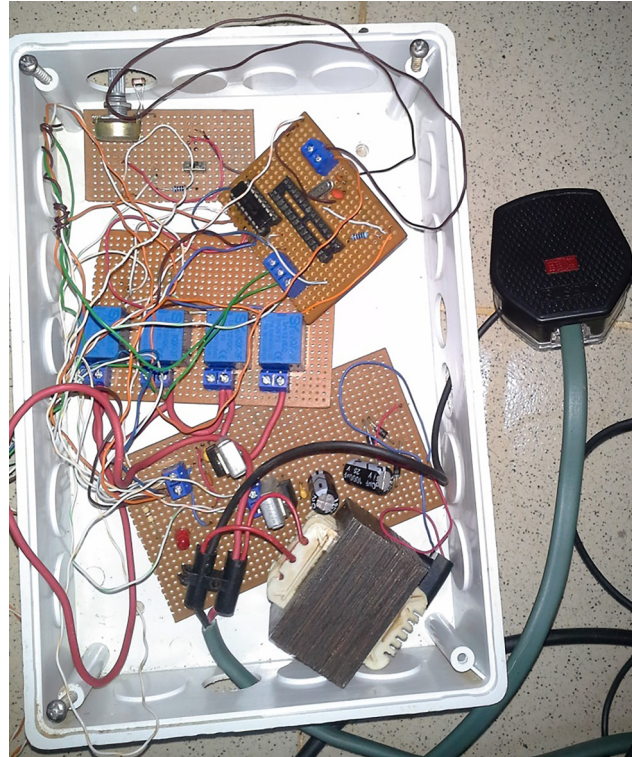


Figure 7: Some of the system electronics.

2.7 Simulation setup

This section describes a MATLAB simulation of a scaled-up version of the designed system using its observed properties and deduced reasonable assumptions, for the purpose of a quantitative performance investigation of the system with respect to two of the major variable factors under which it may be operated, namely, the frequency of occupancy, and the average measured length of occupancy. A two-factor simulated experiment is carried out, with effective length of occupancy having 11 levels, while the frequency of occupancy has 10 levels, resulting in a total of 110 runs of the experiment for all chosen levels of the two parameters. The experiment uses randomisation of conditions where applicable, to give non-deterministic results.

2.7.1 Simulation parameters and method: The system modelled in the simulation is a partially-covered passageway in a 24-h-active office building with 10 individual office entrances leading off the passageway, and 10 separately controlled 40 W luminaires and 10 PIR sensors, such that each light is triggered according to its assigned sensor, operating in insufficient natural lighting conditions for exactly 12 h, from dusk of one day to the dawn of another, modelled and simulated to a time resolution of 1 s.

In the tropical regions, especially near the equator, sunset and sunrise are about 12 h apart. In other regions, over a year, the number of hours of darkness also averages to 12 h a day. Thus, it is assumed that the darkness period during which the artificial illumination system is activated is 12 h.



Figure 8: Assembled project showing luminaires and sensors.

The triggering random events in the simulation of the passageway are new occupancy instances, in which a worker/walker leaves an office/room on the passageway, walks across a section of the passageway or walks the whole length of the passageway and exits the passageway, into another room or exits the passageway completely. These occupancy instances, which are randomised to start at any random timestamps during the 12-h period, and the timestamps are each randomly chosen independently of each other in the 12-h interval by MATLAB's random number generator for each of a 110 runs of the experiment.

Also, the time duration that each walker spends in the passageway is randomly generated such that for each run of the experiment, the durations follow a Pearson distribution with mean occupancy duration of 30 s and standard deviation of 20 s with normal kurtosis and no skewness. Thus, for a traffic density of 50 visits per hour, 600 timestamps are randomly generated and 600 durations are randomly generated for the 12-h interval according to aforementioned rules.

However, the sum of the occupancy retention time built into both the sensor and the microcontroller greatly increase the effective occupancy period with respect to energy usage, and is also accounted for in the simulation as one of the two factors of the experiment. As in reality, the occupancy instances on the passageway may overlap in time. Also randomised is the number of lighting fixtures that are active at any time during the occupancy, which ranges between 1 and 10, and may vary during the duration of the occupancy, according to its recent occupancy history and the path taken, walking speed, loitering time, and distance covered by the worker between his source and destination.

In the system, energy is saved in two ways: by keeping the lights off when the walkway is empty, and also by only turning on lighting fixtures relevant to the journey of the worker/walker through the walkway. If, for example, the worker heads out of his office into an adjacent office, his/her occupancy will only trigger one or two sensors and lights and will last for a few seconds. This way, even if the walkway is constantly occupied, a significant amount of energy can still be saved because not all lights are switched on at all times. Energy saving is further increased if the duty cycle of the walkway is less than 100% (i.e. if there are some times when the walkway is unoccupied, which is usually the case).

As has been mentioned, the two controlled parameters in the experiment are the amount of traffic, measured as the frequency of

walkway visits and the total occupancy retention time built into the sensors and microcontroller. The occupancy retention time is the added time such that if a sensor is triggered and detects a person for d seconds, and the occupancy retention time is s seconds, then the relevant bulb will be activated for ' $d + s$ ' seconds.

The frequency of walkway visits starts at 5 visits/hour (60 visits in total over 12 h) and is increased to 50 visits/hour (600 visits in total) in linear steps of 5 visits per hour, giving 10 different levels of that factor. The occupancy retention time is increased linearly from zero to 300 s (5 min) in steps of 30 s, giving 11 levels of that factor. These then require 110 separate 12-h simulated runs of the experiment.

Thus, each of the 10 levels in the frequency of walkway visits (5, 10, 15, 20, 25, 30, 35, 40, 45, 50 visits/hour) is paired with each of the 11 levels in the occupancy retention time (0, 30, 60, 90, 120, 150, 180, 210, 240, 270, 300 s) and an occupancy profile with a resolution of 1 s is generated for a 12-h period each time. On each of the runs, the occupancy instances' timing and duration are both randomised afresh according to the current levels of the parameters, the number of fixtures active at all points during the duration of each occupancy instance is also appropriately randomised and the occupancy profile records how many lighting fixtures are active in each of the 43200 s for which the simulation accounts. The experiment is made to be as non-deterministic as MATLAB can allow within.

For each run, based on the 12-h occupancy profile, the total energy consumed by lighting fixtures, as well as the percentage energy savings compared to an equivalent but non-automated illumination system can be, and are, computed. The simulation assumes that the system is run constantly, 24 h a day, but that the ambient lighting level is below the set threshold for exactly 12 h daily.

The energy consumption is traditionally computed by integrating the instantaneous power over the period of operation of the system. In this case, since the time is measured in discrete intervals of 1 s, the energy consumption can be computed by summation of the instantaneous power each second over the duration. Hence, the total energy consumption E_t is given as

$$E_t = \sum_{i=1}^I \sum_{k \in K} \eta_i k_i \quad (1)$$

where E_t is the total energy consumed in Watt-second, k is the power rating of a fixture in Watts, i is time in seconds, I is the total time duration, which in this case is 43,200 s (12 h), and $\eta_i \in (0,1)$ is a binary variable indicating the status of fixture k at time instance i and it is given as

$$\eta_i = \begin{cases} 0 & ; \text{ if } k \text{ is inactive at time instance } i \\ 1 & ; \text{ if } k \text{ is active at time instance } i \end{cases} \quad (2)$$

In practice, the value of η_i is determined by the presence of a person in the vicinity of a fixture, such that, it assumes a value of 1 if someone is in the proximity of a device, and a value of 0, if otherwise. Let the total energy consumed in kWh be denoted by $E_t(\text{kWh})$. Then

$$E_t(\text{kWh}) = \frac{1}{60 \times 60 \times 1000} E_t = 2.78 \times 10^{-7} E_t \quad (3)$$

The most energy $E_{\max}$ is consumed when all fixtures are concurrently active during the entire period of evaluation. This is the common case observable in many public passageways. In this case, $E_{\max}$ is computed by setting $\eta_i = 1$ in Eqn. (1) and it is given as

$$E_{\max} = \sum_{i=1}^I \sum_{k \in K} k_i \quad (4)$$

and if expressed in kWh is computed as

$$E_{\max} (\text{kWh}) = 2.78 \times 10^{-7} E_{\max} \quad (5)$$

The percentage energy saved if the proposed energy management system is deployed is computed as

$$E_{\text{saved}} = \frac{E_{\max} (\text{kWh}) - E_t (\text{kWh})}{E_{\max} (\text{kWh})} \times 100\% \quad (6)$$

Choosing parameter value as:

Number of lighting fixtures $|K| = 10$, rating of each fixture $k = 40$ W, and time duration $I = 12$ h (that is 43,200 s), the energy consumption in a scenario without the installation of the proposed energy management system, $E_{\max}(\text{kWh})$ is computed using Eqns. (4) and (5) to give:

$$E_{\max} (\text{kWh}) = 2.78 \times 10^{-7} E_{\max} 2.78 \times 10^{-7} \times 43200 \times 40 \times 10 = 4.8 \text{ kWh}$$

Therefore, 4.8 kWh energy is the baseline to which our simulation experiment is compared to since it indicates the upper bound of the electrical energy consumed under an all-fixtures-active scenario for the 12 h duration under consideration. Simulation experiment was carried out in MATLAB and the computations and some of the data visualisations were done in Microsoft Excel. The plots in Figures 9–17 show the occupancy data when the occupancy retention time is 30 seconds (low), 120 seconds (medium), and 300 seconds (high), for the frequency of visits of 5 visits/hour (low), 20 visits/hour (medium), and 50 visits/hour (high). Specifically, Figures 9 to 11 show the occupancy profile for low occupancy retention time of 30 s, Figures 12 to 14 show the occupancy profile for medium occupancy retention time of 120 s, while Figures 15 to 17 show the occupancy profile for high occupancy retention time of 300 s. Figures, 9, 10, and 11 considers traffic of 5 visits/h, 20 visits/h, and 50 visits/h, respectively, Figures, 12, 13, and 14 also considers traffic of 5 visits/h, 20 visits/h, and 50 visits/h, respectively, and Figures, 15, 16, and 17 considers traffic of 5 visits/h, 20 visits/h, and 50 visits/h, respectively.

The data points are so close in the figures that the individual transitions of the time series data and the per-second changes in the number of active fixtures cannot be effectively visualised but clusters of occupancy period can be seen and give a visual measure of how the energy consumption profile varies with the two parameters (that is,

3 Results and discussions

3.1 Quantitative performance evaluation

The different parts of the model system were tested on breadboard before assembly and found to function as designed, and after assembly, the system was tested by exposing the LDR to light and darkness alternatively while the presence of occupants was introduced by walking slowly across the length of the plywood board to compensate for the reduced scale.

A major qualitative result is that, due to the fact that walkways are transit zones, the major weakness of PIR sensors, in being primarily motion-sensitive occupancy detectors, which are not suited for detecting stationary people over long periods, was found to be avoided to this system.

The system was found to satisfy the design objectives, namely, the use of multiple sensors, spaced along the length of the passageway, to control the selective activation and deactivation of luminaires according to the presence, absence, and position of occupants in the passageway and insufficient natural lighting.

3.2 Computation of energy savings

Sequel to the successful design and implementation of the model system, a simulation-based evaluation of the performance of the system and its energy-saving potential and capability is done to show the efficiency of this multi-sensor multi-actuator passageway illumination system as compared to an equivalent traditional “manual-switch” system. Each of the bulbs used in the study is rated at 40 W, and in a manual switching scheme, it is observed that the bulbs in an external passageway are usually switched on from sunset to shortly after sunrise daily. This period varies but in tropical regions can be as much as 12 h. For the purposes of the simulation, a 12 h period is chosen.

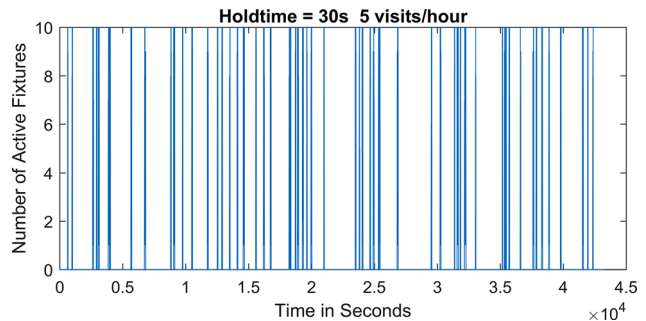


Figure 9: Occupancy profile for low occupancy retention time and low traffic density.

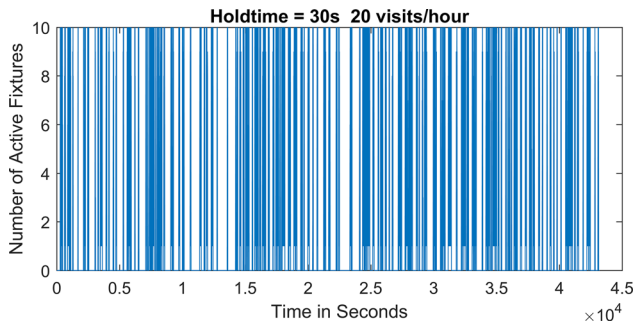


Figure 10: Occupancy profile for low occupancy retention time and medium traffic density.

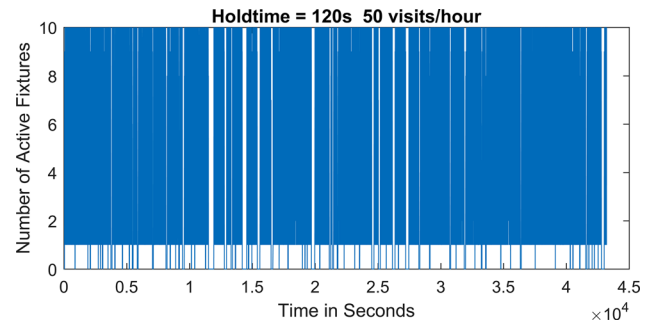


Figure 14: Medium occupancy retention time and high traffic density.

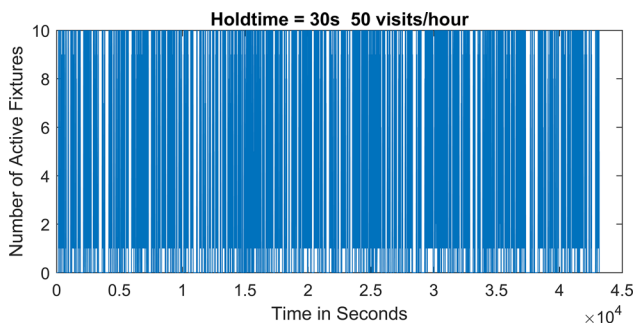


Figure 11: Occupancy profile for low occupancy retention time and high traffic density.

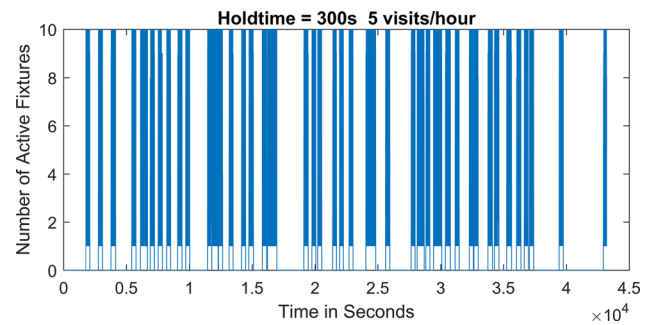


Figure 15: High occupancy retention time and low traffic density.

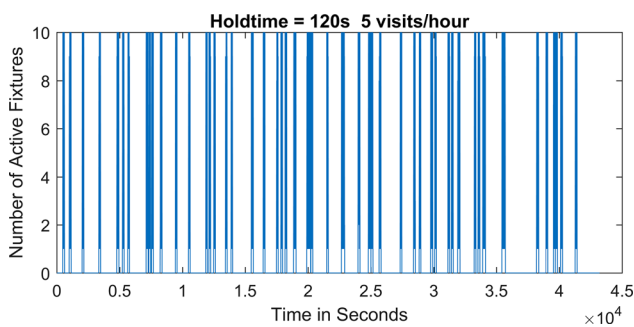


Figure 12: Medium occupancy retention time and low traffic density.

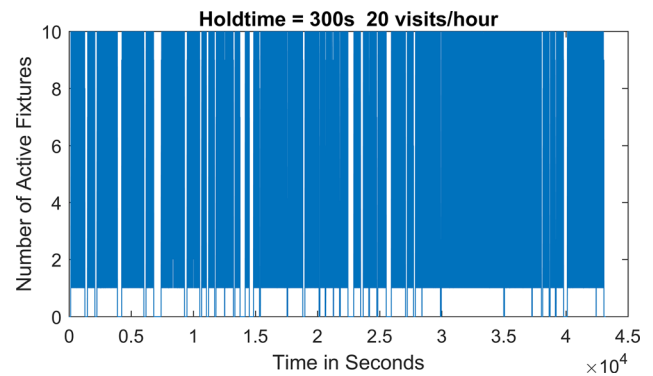


Figure 16: High occupancy retention time and medium traffic density.

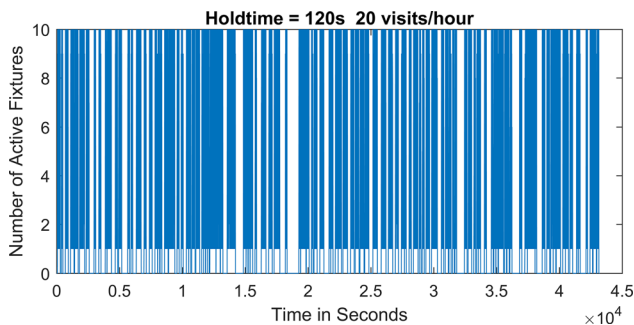


Figure 13: Medium occupancy retention time and medium traffic density.

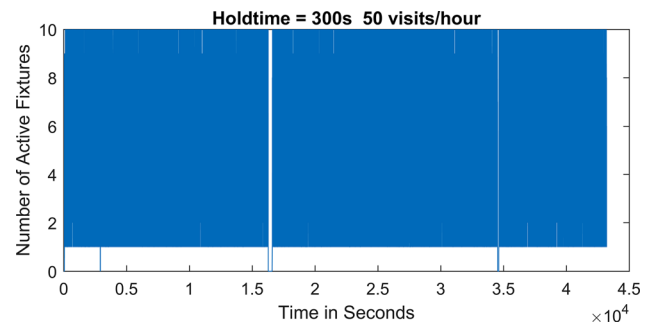


Figure 17: High occupancy retention time and high traffic density.

frequency of visits and occupancy retention time). For example, Figure 9 shows 5×12 , that is, 60 visits in 12 h, with a 30 s occupancy retention period. The arrivals of visits are randomised and this randomisation characteristic accounts for the non-uniform occupancy distribution observable in the graphs. Depending on human proximity to the lighting fixtures, the instantaneous number of active fixtures normally range between 0 and 10 fixtures; although the data points in the graph are so closely packed and are therefore non-reflective of the fact that instances where all 10 fixtures are concurrently active occur only occasionally. Hence all-fixtures-active event is optically exaggerated in the graphs, while the in-between transitions are less visible. For example, in Figure 17, the graph of the occupancy profile at 50 visits/hour with 5 min hold time has an almost 100% duty cycle. The graph's height transits up and down rapidly in resonance with the constantly fluctuating number of active devices per time instance. Since the data points representing the transitions are closely packed, the exact points of transition that corresponds to the current number of active fixtures are unnoticeable but that notwithstanding, some energy is saved as shall be observed in subsequent figures.

Figures 18–20 show the Percentage Energy Savings against the Occupancy Retention Time with each curve corresponding to a certain frequency of visits/density of traffic. It can be observed in Figure 18 that more energy is saved (between 80 and 98% of energy saved) at a low traffic density of 5 visits/h than at a high traffic density (between 53 and 92% of energy saved) of 20 visits/h. If a more critical analysis is done at occupancy retention time of 300 s, it is observable that the margin between the energy saved for traffic of 5 visits/h and 20 visits/h is 27% (that is, 80–53%). This means that an average of 15 visits/h accounts for a whopping 27% of energy consumed at occupancy retention time of 300 s. Stated in another way, 1 additional visit/h accounts for additional 1.8% energy consumption at occupancy retention time of 300 s. This is quite large and we shall see in subsequent graphs (for example, Figure 19) that the additional energy consumption due to additional visits/h diminishes as the traffic density gets higher.

Consider Figure 19; at occupancy retention time of 300 s, the margin between the energy saved for traffic density of 25 visits/h and 35 visits/h is 5% (that is, 52–47%). This means that an average of 10 visits/h accounts for 5% of the energy consumed at occupancy retention time of 300 s. Stated in another way, 1 additional visit/h accounts for additional 0.5% energy consumption at occupancy retention time of 300 s. However, this 0.5% additional energy consumption due to one additional visit is much less than (less than 1/3rd) the 1.8% additional energy consumption

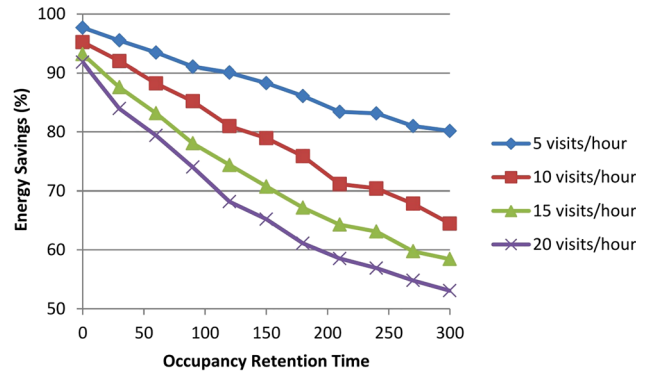


Figure 18: Energy savings vs occupancy retention time with low traffic density.

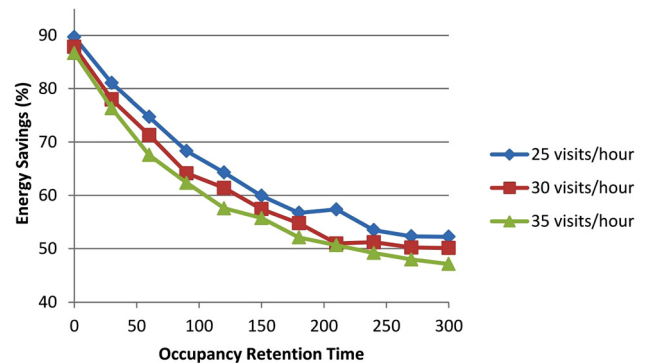


Figure 19: Energy savings vs occupancy retention time with medium traffic density.

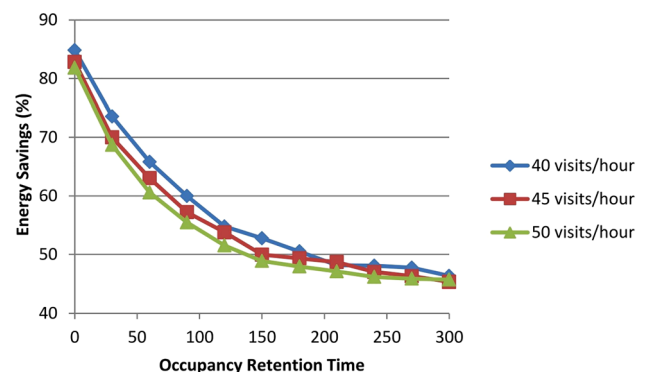


Figure 20: Energy savings vs occupancy retention time with high traffic density.

computed for Figure 18. The important point to note here is that the significance of energy management is amplified at lower traffic density.

Consider Figure 20; at occupancy retention time of 300 s, the margin between the energy saved for traffic of 40 visits/h and 50 visits/h is 1% (that is, 46–45%). This means that an average of 10 visits/h accounts for only 1% of the

energy consumed at occupancy retention time of 300 s. Stated in another way, 1 additional visit/h account for additional 0.1% energy consumption at occupancy retention time of 300 s. This is 1/5th of what was realised at lower traffic density earlier shown in Figure 19. Hence, as traffic density is increased, its impact on the amount of energy saved or consumed diminishes. This information is summarised in Table 1.

Figures 21–23 show how energy savings vary with the frequency of visits for different values of occupancy retention time. It can be observed in Figure 21 that more energy is saved (between 82 and 96% saved) at a low occupancy retention time of 0 s than at high occupancy retention time (between 50.5 and 91% saved) of 90 s. At traffic density of 50 visits/h, the margin between the energy saved for occupancy retention time of 0 s and 90 is 31.5% (that is, 82–50.5%). This means that an average of occupancy retention time of 90 s accounts for a whopping 31.5% of the energy consumed at a traffic density of 50 visits/h. Stated in another way, every 1 s increment in occupancy retention time accounts for additional 0.35% energy consumption at traffic density of 50 visits/h.

Consider Figure 22; at traffic intensity of 50 visits/h, the margin between the energy saved for occupancy retention time of 120 and 180 s is 5% (that is, 52–47%). This means that an average of 60 s of occupancy retention time accounts for a 5% of energy consumption at traffic density of 50 visits/h. Stated in another way, every 1 s increment in occupancy retention time accounts for additional 0.08% increment in energy consumption at traffic intensity of 50 visits/h. This energy consumption associated to every 1 s increment in occupancy retention time is much lower than what was observed for lower occupancy retention period shown in Figure 21.

Consider Figure 23; at traffic density of 50 visits/h, the margin between the energy saved for occupancy retention time of 210 and 300 s is 0.5% (that is, 46.5–46%). This means that an average of 90 s occupancy retention time accounts for 0.5% of energy consumption at traffic density of 50 visits/h. Stated in another way, 1 s increase in

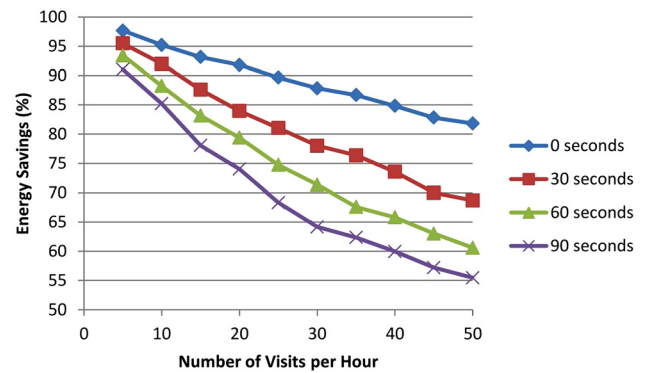


Figure 21: Energy savings vs traffic density with low occupancy retention time.

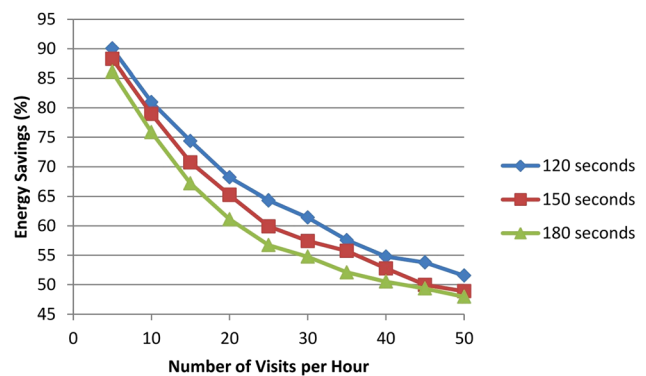


Figure 22: Energy savings vs traffic density with medium occupancy retention time.

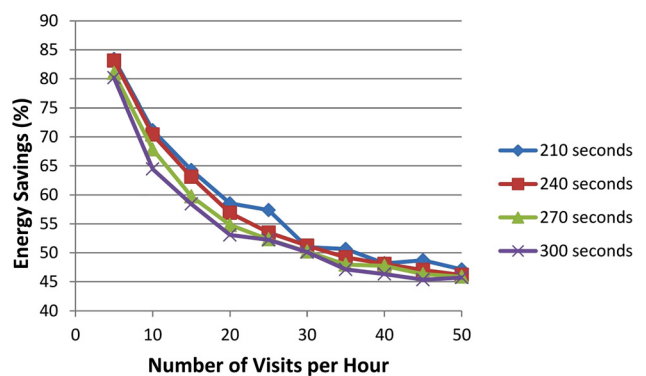


Figure 23: Energy savings vs traffic density with high occupancy retention time.

Table 1: Illustration of relationship between 1 unit of traffic density and the corresponding percentage change in energy consumed.

Traffic density category	Range of traffic density (visits/h)	Percentage energy associated to 1 visit/h traffic density (%)
Low	5–20	1.8
Medium	25–35	0.5
High	40–50	0.1

occupancy retention time account for additional 0.006% energy consumption at traffic density 50 visits/h. This is much lower than what was observed for lower occupancy retention period in Figures 21 and 22. Hence, as occupancy retention time is increased, its impact on the amount of energy saved or consumed diminishes. This information is summarised in Table 2.

Table 2: Illustration of relationship between 1 unit of occupancy retention time and the corresponding percentage change in energy consumed.

Occupancy retention time category	Range of occupancy time (s)	Percentage energy associated to 1 s of occupancy retention time (%)
Low	0–90	0.35
Medium	120–180	0.08
High	210–300	0.006

It can be summarised that the energy savings generally decreases with passageway traffic density and can be increased by decreasing the occupancy retention time. In practice, the occupancy retention time should be tailored according to the density of traffic for optimal efficiency of the passageway illumination system, and combinations of extremely high values of these parameters are discouraged unless necessary for the specific application. Walkways with high traffic areas will generally provide more energy savings with lesser occupancy retention periods. On the other hand, low-traffic passageways tend to provide high energy savings for a wide range of occupancy retention times, even though lower occupancy retention times are generally more efficient than higher occupancy retention times.

4 Conclusion

An automatic energy management system for passageway illumination using occupancy-sensing technology has been designed and implemented and the performance of the system investigated by both testing the constructed version and also performing scaled-up simulations. Based on results of extensive simulations, the system promises significant passageway energy savings of 45–95% (as seen in Figures 18 to 23) for a wide range of situations in passageway illumination systems. In particular, significant energy savings are achieved while strictly ensuring that the quality of illumination service to passersby is in no way compromised, thanks to an array of roof-mounted passive infrared sensors that sense the presence, absence, and positions of occupants on the covered area of the walkway. In addition, the implemented system was found to be capable of saving energy even when the walkway is constantly occupied, due to the selective energization of the luminaires relevant to the movement of the occupants of the walkway.

This work, which is applicable to both AC and DC grids, provides an invaluable insight into the extent of savings in

electrical energy that is achievable in an occupancy-based energy management system and, if incorporated in energy consumers' facilities, could save them significant financial costs on electrical energy consumption by reducing the volume of energy that is wasted when illumination service is unnecessary through automated activation and deactivation of lighting fixtures.

5 Limitations and recommendations for future work

A major limitation of this work is that the ATmega328P microcontroller that was employed has only 14 digital I/O pins, which implies that it can be used with only 14 lighting fixtures. This makes the current configuration of our design clearly incapable of large scale implementation. However, this can easily be addressed by the combined use of the SPI (Serial Parallel Interface) protocol of ATmega328P and shift registers chips, for example, 74HC595 chip. This will involve only a minor modification to our circuit such that, instead of connecting each of the lighting fixtures to an I/O pin of the ATmega328P microcontroller, they will each be connected to a pinout on the 74HC595 chip, which in turn will be connected to only three I/O pins on the microcontroller. The 74HC595 chip has an internal 8 bit latch that makes its output stable until a new data is latched. With the input signals "Serial-Data-In", "Serial-Clock" and "Latch-Clock" sent to it from the microcontroller, it is able to control eight outputs, or in our case, eight lighting fixtures. Hence, daisy-chaining (by connecting the Serial-Out pin of one to the Serial-Data-In pin of the next one) four 74HC595 chips makes it possible to control 32 luminaires with only three digital I/O pins on the microcontroller. Likewise, if nine 74HC595 chips are daisy-chained, it will be possible to control 72 lighting fixtures with only three digital I/O pins on the microcontroller, and so on.

A full-scale implementation of this work requires that an existing operational office building of a public or private organisation be obtained and retrofitted electrically. It also requires volunteers' cooperation in order to facilitate the logging of relevant data. All these would require so much time, money, and access permission to real estate; hence, the full scale implementation of our idea has been considered as the subject of future work, while its simulation has been conducted and presented in this paper.

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Appendix

Table 3: Bill of engineering measurement and evaluation (BEME).

Item	Description	Quantity	Unit price (\$)	Amount (\$)
Microcontroller	ATMega328P-PU	1	1.90	1.90
Transformer	12 V 1 A	1	3.28	3.28
Electrolytic capacitor	1 mF, 25 V	2	0.73	1.46
Ceramic capacitor	Non-polarised capacitors	6	0.02	0.12
Crystal oscillator	16 MHz crystal	1	0.18	0.18
Electromagnetic relay	12 V relay	4	0.98	3.92
Rectifier diodes	IN4004	4	0.10	0.40
PIR sensors	HC-SR501	3	1.54	4.62
Resistors	Carbon	3	0.02	0.06
LED	Low power (5 V)	1	0.02	0.02
Voltage regulator IC	LM7800 series	2	0.51	1.02
Heat sinks	TO-220 heat sink	2	0.26	0.52
Potentiometer	Low power (5 V)	1	0.02	0.02
LDR	Low power (5 V)	1	0.02	0.02
Power cables	1.5 mm ² cable yards (twin core)	8	0.20	1.60
Toggle switch	Sliding knob	20	0.01	0.20
Transistor array IC	ULN 2003 IC	1	0.25	0.25
Lighting fixtures	40 W bulbs	4	0.25	1.00
Jumper wire	UTP cable (yards)	4	0.25	1.00
Solder	60/40 flux core	1	1.00	1.00
PCB-screw terminals	Grouped units	17	0.02	0.34
Terminal blocks	Connector	2	0.08	0.16
Plywood for mounting lights	4 ft by 2 ft	1	3.90	3.90
Lampholders	Pin type socket	4	0.33	1.32
DIP IC sockets	Solderable IC socket	2	0.10	0.20
Board	VeroBoard	3	0.33	0.99
3-Pin plug	2 A fused plug	1	0.52	0.52
Packaging	Terminal box	1	2.00	2.00
Total				32.02

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