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Design And Construction Of The Circuits For An Iot-Based, Stand-Alone, Solar Powered Street Light With Vandalisation Monitoring And Tracking Mechanism

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Abstract— **In this paper, the design and construction of the circuits for an IoT-based, stand-alone, solar powered street light with vandalisation monitoring/tracking mechanism is presented. The entire system circuit consists of two major sub-circuits. One of them is basically for vandalisation tracking employing the Electron 3G IoT module and the tracking is implemented using triangulation approach. The other circuitry generally is designed to achieve energy saving, as well as remote vandalisation monitoring. The circuits have two major sections which are; the power section and the sensor/intelligent section. This system focuses on power conservation, energy efficiency, compact size, automation and intelligence, and ultimately, vandalisation monitoring. The system is designed in such a way that it automatically switches the street light ON and OFF by the application of the light dependent resistor (LDR). In addition, it also saves power by utilizing infrared (IR) sensors together with the Arduino Wi-Fi module to control the dimming and brightening of the street light thereby increasing the overall life span of the LED array. Finally, the design includes creating a user interface (UI) to aid remote vandalisation monitoring whereby the street lights can communicate with control persons at the control station via Wi-Fi. This is achieved with the ESP8266MOD Arduino Wi-Fi module which serves as the controller (brain) of the system. The system uses a 20W, 18V solar panel and has a battery bank of capacity 19.8Ah. The module used for lighting is a 32-bit LED array. Lithium-ion batteries were used in this work and they require a lot of carefulness since over-charging can result in fire explosions. Therefore, the power section of the design includes LM 2596 and LM 317 regulators which serve as the solar charge controllers at constant voltage and constant current respectively, to check the charging and discharging function of the batteries. The circuits were designed employing the DipTrace software and the Printed Circuit Board (PCB) design. Implementation was done by employing the process of etching.**

Keywords—Triangulation, Base station, GSM module, GPS, Arduino Wi-Fi module, Internet of Things (IoT), IR sensor module, Light Dependent Resistor (LDR), LED array, Wi-Fi, lithium batteries, Depth of Discharge (DoD) User Interface (UI), Smart, ULN2003 Driver

I. INTRODUCTION

Street light is a raised source of light on the edge of a path or road. The main purpose of street lighting is to illuminate the environment during the night time. Nowadays, to avoid accidents and provide general safety along the roads, street lighting is a major requirement [1]. Street lights play an important role in reducing risks of night time accidents, discouraging crime and enhancing the security of an environment for habitation. The different types of street lights include: Metal halide street lights which are very brightly coloured street lights [2], High Pressure Sodium (HPS) street lights which are high intensity discharge lamps. HPS is the most commonly used street lights in many countries all over the world, Low Pressure Sodium (LPS) street lights, Light Emitting Diode (LED) street lights which are very efficient in energy savings and produce more light than incandescent bulbs [3] among others.

Notably, the need for sustainable and cleaner energy sources has necessitated the exploration of available renewable energy sources. Renewable energy is generated from natural sources such as; wind, sun, rain, tides, and can be generated repeatedly because they are abundantly available. They are, by far the cleanest sources of energy that are naturally available on the planet [4]. The need to provide sustainable power supply and curb vandalisation of street lights necessitated this study. The system is solar powered, with a battery bank to store energy for later use. The batteries used here are the cylindrical lithium batteries which have a good Depth of Discharge (DoD) and have higher energy densities. Their charging and discharging functionalities need to be critically considered since over-charging can result in fire explosions and over-discharging can reduce the overall performance of the batteries, hence shorten its lifespan. It also takes advantage of the emerging internet of things (IoT) technology to carry out remote vandalisation monitoring/tracking. The ESP8266MOD module used in this design is based on the ATMega328P with an ESP8266 Wi-Fi module integrated in it. It has integrated TCP/IP protocol stack that gives access to Wi-Fi network. This module is needful in providing support for Over-The-Air (OTA) programming and transmission. The system makes use of two IR sensor modules, one for sensing vehicular movement (car-sense), and the other for sensing the presence of human, a possible theft threat (human-sense). Essentially, the human-sense IR, following a pre-set program, triggers an alarm when it senses human presence. The purpose of the alarm is to alert the locals of the area of a possible theft and ward off the vandal.

II. METHODOLOGY

First, the requisite meteorological data for the case study site was acquired after which the daily load demand for the stand alone street light system was determined [5, 6]. The meteorological data for the case study site and the daily load profile are the basis on which the sizing of the PV array was done. Sizing of the battery (stoarge bank) was carried out based on the days of autonomy (3 days) after which sizing the capacity of the solar charge controller was done. Secondly, the circuits were developed using the DipTrace software and printed on a PCB sheet then the process of press-and-peel was carried out. Thirdly, the process of etching was done and the board was drilled. Lastly, the different components were mounted on the board and the whole system was assembleda.

A. Features of the Proposed System

The components used in this design are: Arduino Wi-Fi module (ESP2866MOD), IOT module (Particle Electron 3G), Flying Fish infrared sensor (IR) module with adjustable distance, ULN2003 driver IC, LED array, LDR, SARODA SP09-05 model solar panel rated 18V, 20W,18650 cylindrical lithium-ion batteries rated 2200mAh, 3.7V a computer and a wireless router. The schematic representation of the entire system is presented in Figure 1.

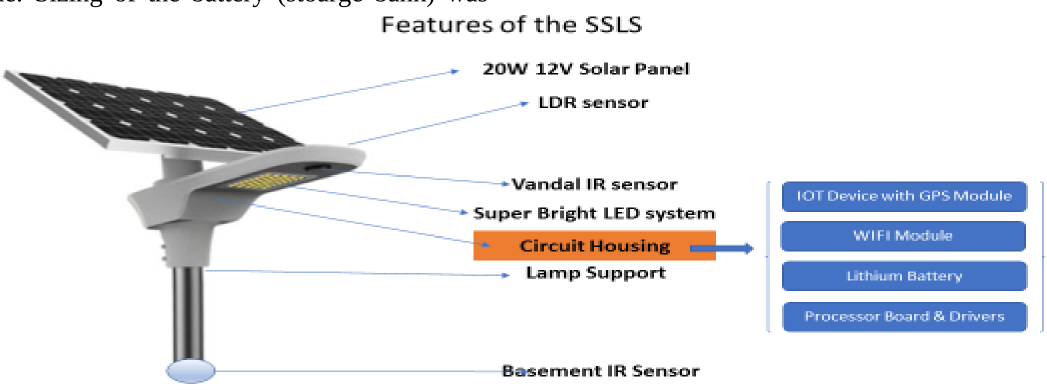

Figure 1. Features of the proposed system

B. Working Principle of the Infrared (IR) Sensor Module

The IR sensors in this work perform two separate functions. From 11pm, the car-sense IR senses vehicular movement to brighten up the light and hold it for 2 minutes till the car passes, after which it switches back to the "DIM" state. The secon IR sensor (human sense), senses the presence of a vandal few centimetres close to the top of the installation and triggers the alarm while the system and OTA to the control station in real time. A schematic showing the working principle of the IR sensor is presented in Figure 2 .The IR sensor module chosen for this design is the Flyng Fish Module FC-51 model and has a detection distance of 2 ~ 30cm and aworking voltage: 3 - 5VDC [7].

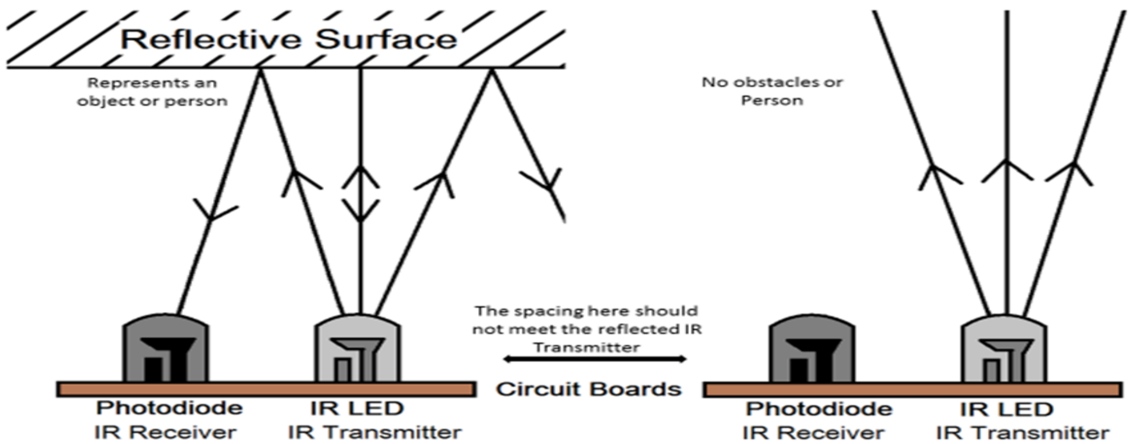

Figure 2. A schematic of the working principle of the IR sensor

C. IoT Tracking Mechanism

The IoT/tracking section of the design is dependent on embedded systems that communicate with one another and the cloud. The transmitted data is processed by a set of program installed on the IoT device which allows the system to make certain decisions and perform certain action. This decision allows the system to perform such actions as, sending an Over the Air (OTA) message to the control station and automatically adjusting the devices/sensors without the need for human inputs. The circuit design for the vandalisation tracking is as presented in Figure 3.

In this circuit, there are two IR sensors. One is tagged "human-sense" while the other is tagged "car-sense". The human-sense IR is controlled by a time-based (11pm) program to allow for remote over-the- air [OTA] transmission to the IoT whenever there is a security threat on the installation. Once IR (human-sense)senses a possible vandalisation threat, it send an OTA message to the control station for operatives to take action. In a situation where the vandal is able to make away with any part of the installation, the IoT will be used to track the vandal via a method called "triangulation". Triangulation is defined as a process by which a radio transmitter's location is determined by either measuring the radial distance or the direction of the received signal from two or three base stations [8]. This process is used to pinpoint the geographic location of a cell phone. Triangulation is also based on trigonometric proposition. This is a process of determining coordinates of vertices of figures using one known side and two known angles [9, 10]. The distance (d) of the object from a point situated at the baseline (*l*) is determined thus [11]:

$$d = l \frac{\sin\alpha \; x \; \sin\beta}{\sin(\alpha + \beta)} \quad (1)$$

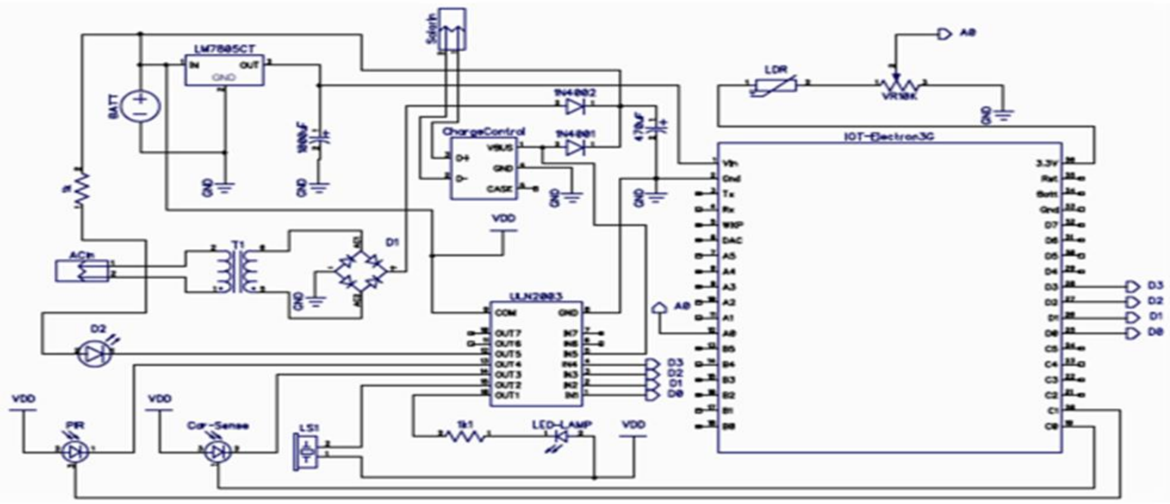

Figure 3. Circuit diagram of the IoT tracking mechanism

The distance between two masts can be known because nowadays, all existing communication masts owned by different network providers have their coordinates on the Google satellite. The distance between two known masts in relation with the IoT module that is being tracked is known as the baseline denoted as *l* in(1). The IoT module is embedded with a GSM module, hence has GPS features. In order to track the IoT module, the network masts detect the Region of Interest (RoI) using the GPS transmission of the IoT in a triangular manner as presented in Figure 4. Through a special algorithm which includes Network Measurement Report (NMR) which contains all the cell information, and signal strengths, the system calculates the distance of the IoT device from a point located at right angles to the baseline. This measurement predictsa more precise location of the IoT module which is housed in the installation part that is being tracked. All of these is achieved by a set of pre-programmed instructions installed in the IoT device.

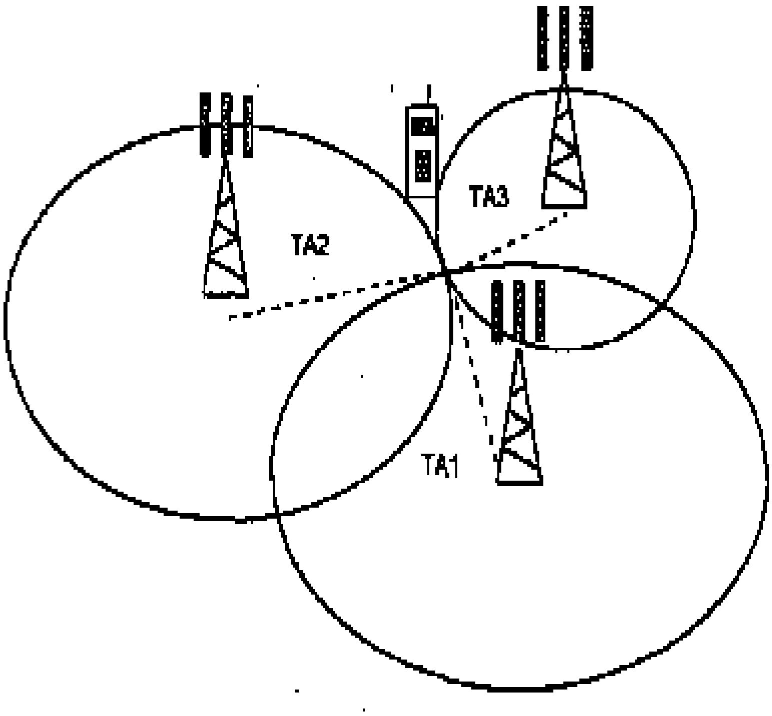

Figure 4. Triangulation process of a mobile device

The circuit diagram of the smart and compact stand-alone street light is comprised of different modular circuits encapsulated into one. The circuits has two major sections which are; the power section and the sensor/intelligent section. The rest of the components are the buzzer and the ULN2003 chip which basically employs the transistor-transistor-logic (TTL). Innovation has brought about the advent of fully programmable IC chips and this has lessened, or almost eliminated the need for calculations in circuits. Nowadays, the calculations are converted into source codes and uploaded into the programmable chips. The different segments of the circuit are discussed in the following sections. The circuit diagram of the entire stand-alone street light is as presented in Figure 5.

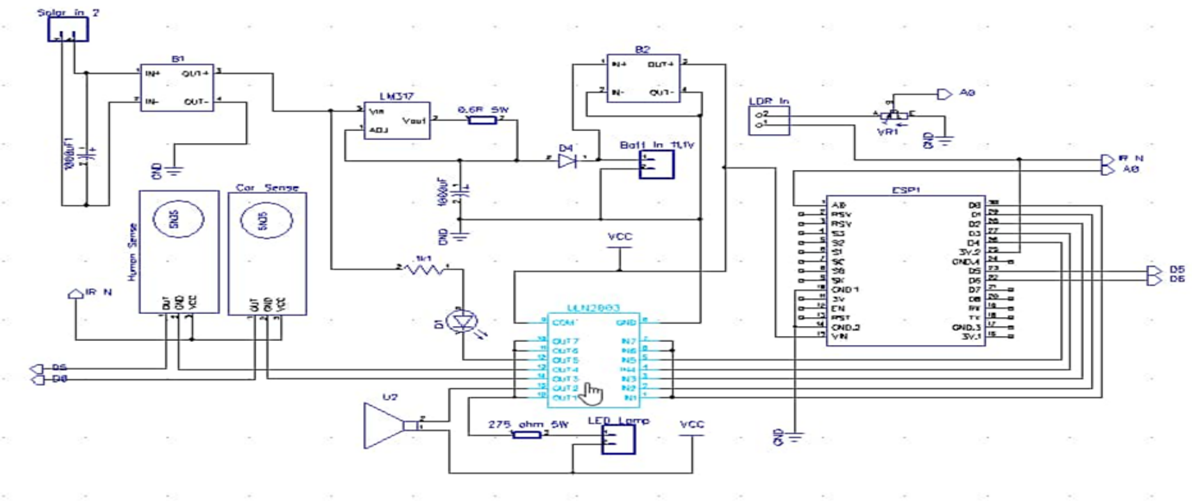

Figure 5. Circuit diagram of the stand-alone street light.

D. Power Section

The power section comprises of the solar PV module rated at 20 W, 18 V, two LM2596 variable switching regulators denoted as B1 and B2, LM 317 which is a constant current regulator, a power bank of Lithium-ion batteries rated 19.8Ah, 11.1 V, a diode and a resistor. The power section of the design is presented in Figure 6. The regulators (LM 2596, LM 317) serve as the solar charge controllers at constant voltage and constant current respectively, to check the charging and discharging function of the batteries.

Firstly, unregulated signal of 18V comes in from the solar panel. This signal is full of noise in form of ripples due to the unstable weather conditions therefore a capacitor with an ambient value of 1000µF is used to filter this signal of noise. In this work, three batteries of cell rating 2.2Ah, 3.7V are being combined in series to give the required power. Most consumer oriented lithium ion batteries charge up to a maximum voltage of 4.2V per cell with a tolerance of 50mV (plus or minus) [12, 13, 14]. Therefore, the required system voltage is given as:

$$System\ Voltage = max.charge\ voltage\ per\ cell\ x\ number\ of\ cells\ in\ series \quad (2)$$

= 4.2 x 3 = 12.6 V

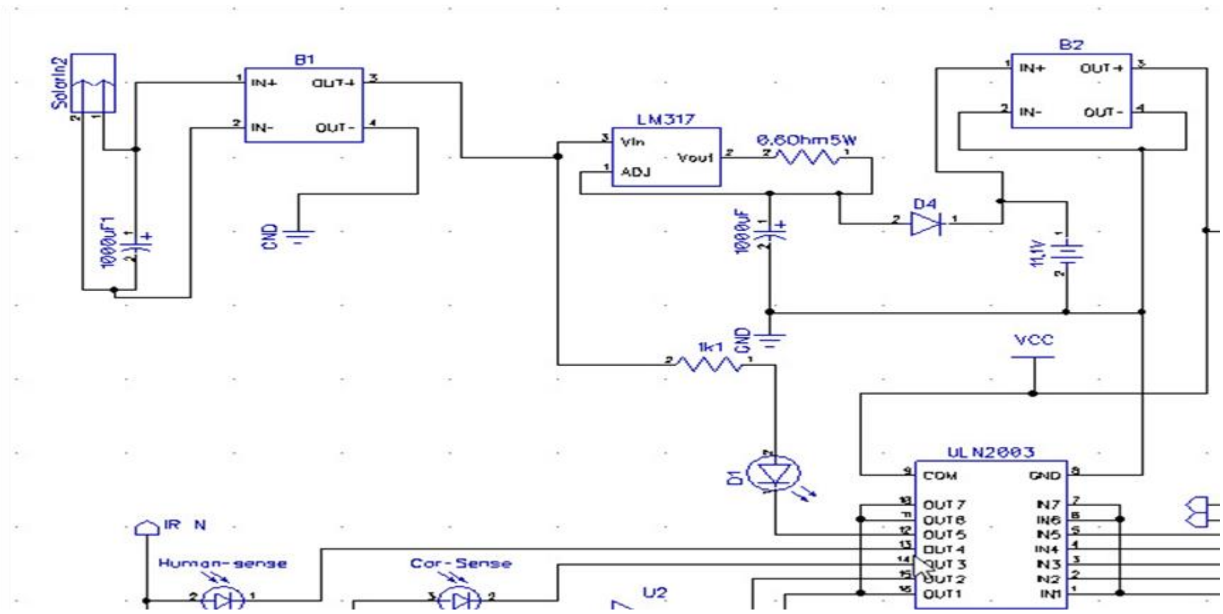

Figure 6. Power supply section of the circuit design

It is therefore safe to choose 12 V as the required regulated voltage coming into the circuit. With this, the LM 2596 (BI) in Figure 3 (the power supply section of circuit) is tuned to regulate the input voltage to a constant voltage of 12 V. In other words, the regulator sets the voltage limit at 12V, so at any point, the batteries will not experience any voltage more than 12V. The regulated 12V goes out via pin 3 of the regulator to V_{in} (pin 3) of the constant current regulator (LM 317). Since the battery is rated at 2.2A per cell, it is required that a constant charge of 2A be used to charge the batteries. The internal reference voltage of the LM 317 is 1.25V. Since a constant charging current of 2A is required, to determine the amount of resistance needed to produce only 2A for charging, Ohms law is therefore applied as follows [15]:

$$V = IR \quad (3)$$

Where V = 1.25 V, I = 2 A

$$R = \frac{V}{I} \quad (4)$$

$$R = \frac{1.25}{2} = 0.63\Omega$$

There is hardly a 0.63Ω resistor, hence the next higher or lower value is chosen, 0.43Ω. This 0.43Ω resistor creates a resistance such that the total current going in to charge the batteries does not exceed 2A. Once the battery is fully charged, the charge begins to trickle (trickle charging). However, the trickle current is not harmful to the batteries. The 2A output current is fed back to the adjust pin (ADJ) of the LM317. The feedback process ensures that the current is maintained at 2A. However, there is still the presence of noise/ripples in this current, so it is filtered by a 1000µF capacitor to get rid of the noise. A diode is connected in series with the batteries to prevent reverse voltage. The constant current regulator is very important in this circuit to limit the current charging the batteries to avoid over-charging and possible explosion. The minimum discharge level for these lithium-ion batteries is 2.8V to 3.0V [12]. Recalling that in this work there are three batteries in series, the minimum discharge voltage would be 8.4V. The potential difference across the cells would be:

$$12 – 8.4 = 3.6V$$

From the datasheet, the cell resistance of the battery is about 23mΩ. Assuming there is no current limiting device, the theoretical current is given by applying (3) as:

$$I = \frac{V}{R} \quad (5)$$

$$I = \frac{3.6}{0.023} = 156.5A.$$

Obviously, 156.5A is too high to pass through the electronic circuit. It would burn the system. This proves why the current limiting regulator is needful. However, once the battery charges up to 12V, the potential difference are zero so ideally, no current should flow. Nevertheless, this is not so. There will still be trickles of current, about 1mA, flowing to the batteries.

The current flows through output V_{out} (pin 2 of the LM 317) to charge the batteries. At this point, a diode is connected in series with the batteries to avoid reverse voltage. The 11.1V goes into the power pin (pin 1) of the second variable switching regulator B2. The regulator, unlike the first one, is tuned to regulate the voltage to 5V which is required to power the electronic boards. Lastly, an appropriate heat sink is installed in the circuit board to expel the heat generated in the system in order to prevent premature failure of the LED lamp.

C. The Sensor/Intelligence Section

The sensor/intelligence section comprises of the Arduino Wi-Fi module, the IR sensors, the buzzer, LED array rated at 6V, 3.2W, the LDR and the ULN2003 driver as shown in Figure 7. The regulated 5V output from pin 3 of the LM2596 feeds into the main positive supply (V_{in}) of the Arduino Wi-Fi module and this is what powers the board. The Wi-Fi module further regulates the received 5V to 3.3V which is a safe voltage to power the LDR and the required voltage rating for the IR sensors. It is important to power the LDR with 3.3V so that in case a higher voltage is mistakenly fed in through the analog pin (A0), the Wi-Fi board would not be damaged. When the weather is very bright, the resistance of the LDR turns low, therefore the voltage is high and vice versa. This voltage is fed into the analog pin (A0) of the Wi-Fi module which is programmed to turn on the street light on receiving a certain pre-set voltage. Outputs D0 to D4 on the Wi-Fi module are bi-directional control pins, but are set to be uni-directional output pins in this work. ULN2003 is basically an IC chip of transistors which is powered by its common (COM) and ground (GND) pins by 5V directly from the 5 V regulating LM2596. D1 is an LED that blinks to show that charging is ongoing.

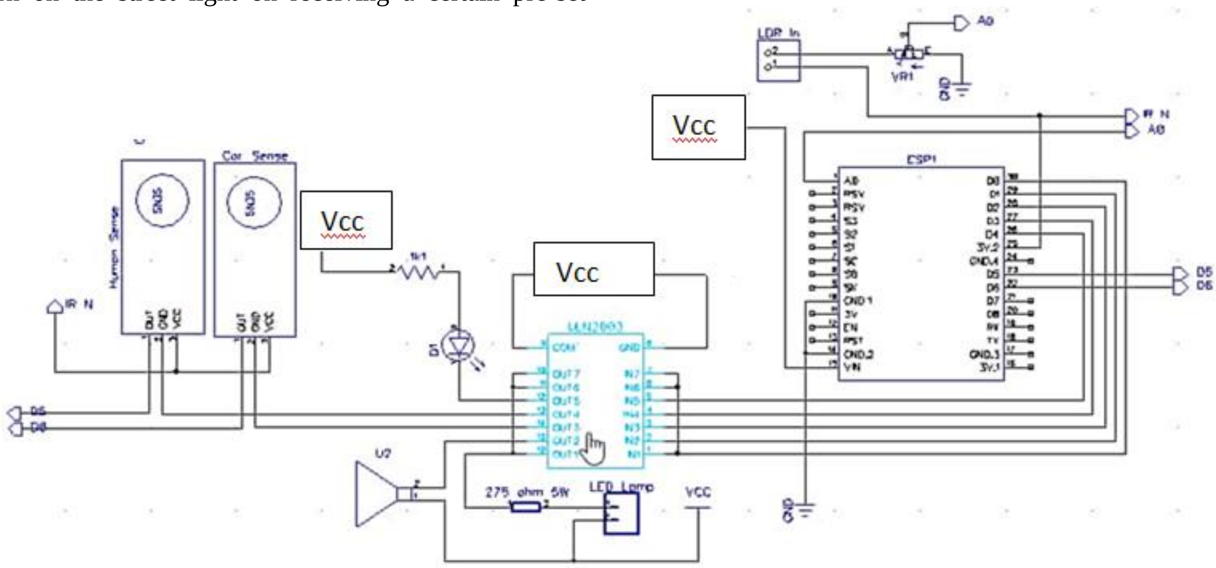

Figure 7. The sensor/intelligence section

The datasheet of the ULN2003 driver records that its maximum output clamp current is 0.5A. The input voltage of the LED lamp is 6V. Its power output is 3.2W. In order to determine how many pins of the driver can be used to power the lamp, (4) is applied thus:

$$I = \frac{P}{V} \qquad (6)$$

Where V = 6V, and P = 3.2W, then , $I = \frac{3.2}{6} = 0.53A$.

This means that the current that will be flowing through one pin is 0.53A. This is obviously a bit higher than the rated maximum current of the driver. To allow for a safe flow of current, three pins are connected together as seen in the circuit diagram in Figure 4, totaling (0.5 + 0.5 + 0.5 = 1.5A). With this connection, the LED lamp can be safely powered by the driver without burning out any pin. Again, a resistor is connected in series with the LED lamp to limit the power flowing across the lamp. The value of resistor to be used is determined as follows:

$$R = \frac{V_{res}}{I_{res}} \qquad (7)$$

Where I_{res} is the current across resistor and is determined by calculating 60% of I_f [16]. I_f is the maximum forward current of the resistor and is usually 20mA. Therefore, I_{res} gives 12 mA. The voltage drop (V_{res}) across the resistor is given as:

$$V_{res} = V_{batt} - V_f \qquad (8)$$

Where V_{batt} is the battery voltage (11.1V), and V_f is the forward voltage drop across the LED usually between 1.8V to 2.2V. The LED lamp chosen for this work is arranged in a 4S8P combination. Hence there are four resistors connected in series with a forward voltage drop of 1.8 x 4 = 7.2V (considering minimum V_f).

$$V_{res} = 11.1 - 7.8 \ = 3.3V$$

Since all variables are known, therefore applying (5) gives:

$$R = \frac{3.3}{0.012} \ = 275\Omega$$

Therefore, the ideal value of the current limiting resistor to be connected in series with the LED array is 275Ω or the next higher value of standard resistors. When the LDR senses darkness, its resistance increases and it feeds a low voltage to the analog pin of the Arduino Wi-Fi module (A0). When the Wi-Fi module receives this input, it instructs pin 15 (D0) to switch to a high state. This high signal is then fed into the driver at pin 16 (IN1) which in turn sends a low signal through pin 16 (OUT 1) to turn on the LED lamp. Subsequently, when the LDR senses enough daylight, (say from 6 am), its resistance becomes low, and it sends a high voltage to the analog pin of the Wi-Fi module. As the module receives this high voltage, it instructs pin 15 (D0) to switch to a low state. This low signal is then fed into the driver at pin 16 (IN1) which in turn sends a high signal at OUT 1 to turn off the light. In order to achieve energy saving, a program is uploaded to the Arduino Wi-Fi board such that from 11pm, when there is less traffic and minimal road usage by pedestrians, the street lights switches to a dim state but switches back to its full bright state on sensing vehicular movement. The sensor that does the vehicle sensing is the “car-sense” IR module. When this sensor picks up IR reflections from a moving vehicle, it triggers pin D6 of the Wi-Fi board and the board sends a command to turn the light from dim state to full bright state. These dimming and brightening functions are achieved through pulse width modulation.

The other IR sensor is tagged “human-sense”. The purpose of this IR sensor module is to detect possible theft threat by sensing human presence 15cm close to the top of the street light installation. When human presence is sensed, it sends a signal through D5 to the Wi-Fi module which by a pre-set program, triggers the buzzer which would alert the locals of that location. At the same time, an over the air (OTA) message is sent to the control station, alerting the operator of a possible theft. Both IR sensor modules are powered by 3.3V VCC via the pins denoted as IR-N as shown in Figure 5. The system is also able to detect a faulty street light and send notifications to the control station.

D. Construction of the Circuit

The following materials were used for the construction of this work: press and peel paper, copper cloud board, pressing iron, ferric chloride anhydrous and hot water. The different steps taken during the construction are; printing of the PCB design, preparation of the Copper Cloud Board, imprinting on the copper cloud board, etching process, drilling, mounting and assembly.

PCB Design of the Circuit

The PCB design as printed out is presented in Figure 8. The copper cloud board was cut according to the size of the PCB print-out. After cutting, the surface was scrubbed with an abrasive paper and washed. This process ensures that the board has a clean surface which is necessary to achieve a good print on the board. The cut and cleaned board is as seen in Figure 9.

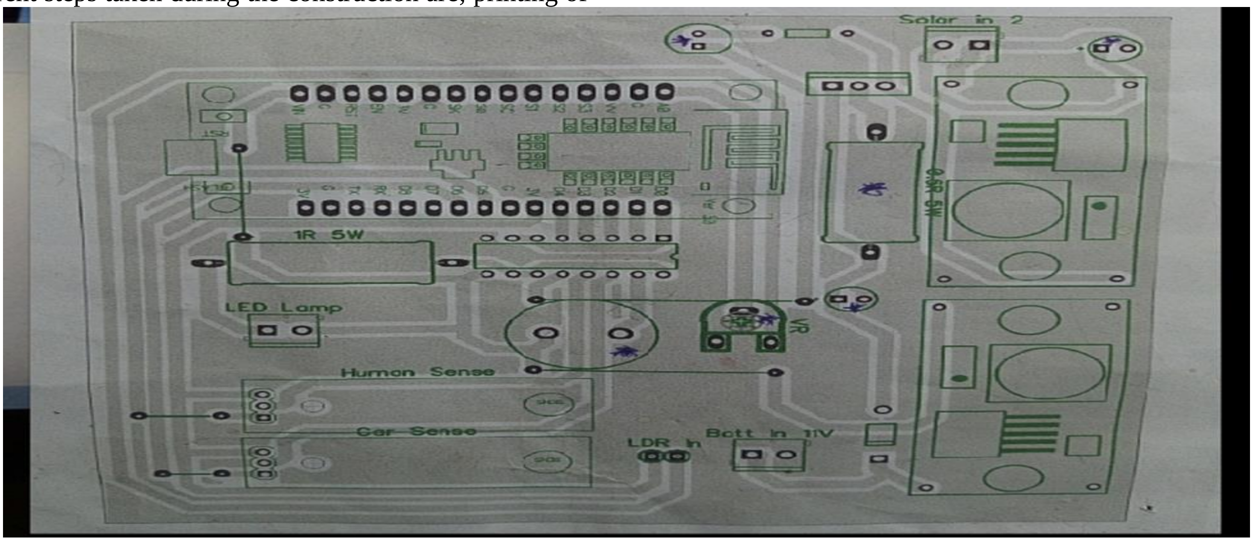

Figure 8. Printout of PCB design

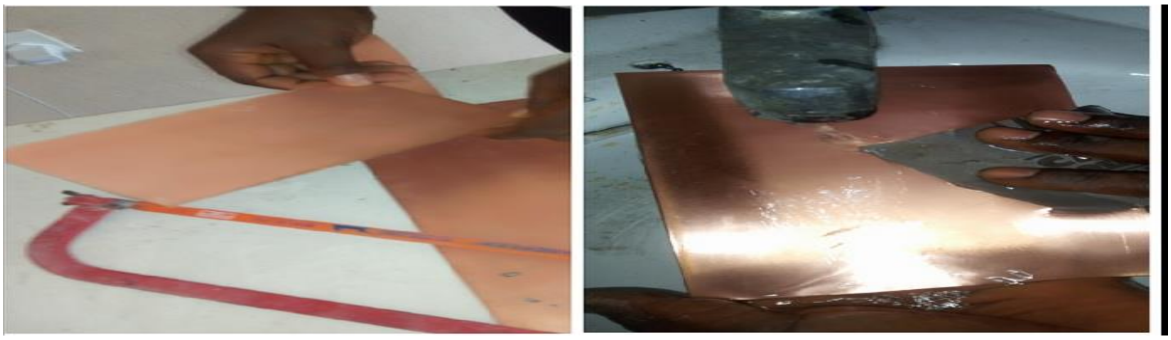

Figure 9 Preparation of the copper cloud board

Imprinting on the Copper Cloud Board

The next step involves imprinting the PCB design on the copper cloud board. This was achieved by using a pressing iron to hard press the printout on the board as shown in Figure 10. After pressing, the PCB sheet is peeled off leaving only the connection lines on the board.

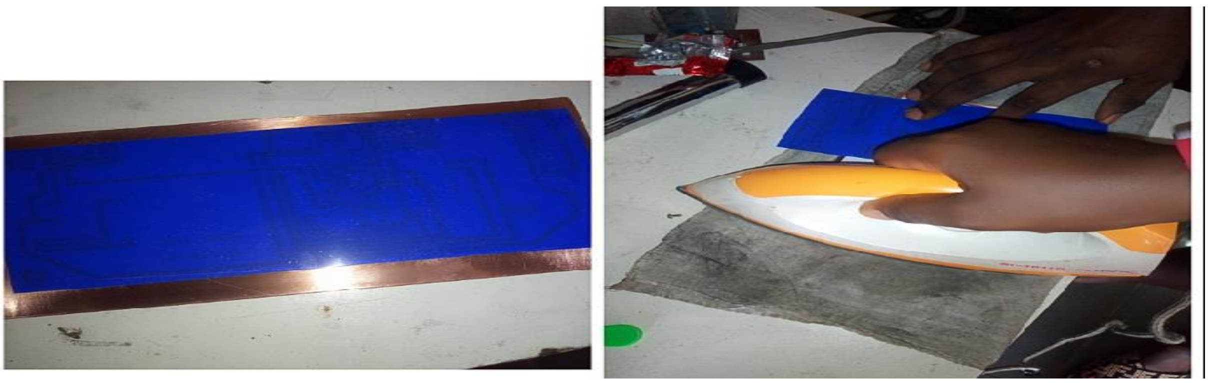

Figure 10. Imprinting on the PCB board

Etching Process

Etching is the process of using strong acid to cut into unmarked or unprotected prats of a metal in order to create a design. In this work, the acid used was ferric chloride anhydrous mixed with hot water. The printed board was dipped into the mixture for about five minutes as shown in Figure 11. After five minutes, the board is removed and washed with soap and water to get rid of all the residual acid. This process removes all the copper on the board except the parts preserved by the design.

Figure 11. Etching process

Drilling, Mounting and Assembly Process

This process involves using a drilling machine to bore holes in the board. The components are soldered or mounted on the holes. The assembled board is as shown in Figure 12. Finally, the whole system is assembled in its casing.

Figure 12. The assembled board

Battery Equalisation and Combination

The lithium batteries were first of all, connected in parallel and charged using a DC power supply at 3.8 V. It is important to match the capacity of the batteries before combining in order to ensure optimum performance and preserve the battery life. After equalisation, the batteries were arranged in parallel and glued together using a glue gun as shown in Figure 13. Thereafter, the batteries were soldered together using a conducting metal.

Figure 13. Battery equalisation and arrangement

III.RESULTS AND DISCUSSIONS

The requisite meteorological data for Uyo metropolis which showed clearly, the months of lowest solar irradiation in Akwa Ibom State as July and August, was retrieved from the NASA website. The daily load profile of the system was determined to be 44.5Wh/day, while the required minimum battery capacity was calculated to be 16.4Ah. However, in this work 19.8Ah was chosen for ease of battery equalisation and balancing. The month with the lowest solar irradiation, which according to the meteorological data is August, together with the calculated daily load profile of the system, were taken into consideration in sizing the solar PV module. The required capacity for the solar PV module is 15.02W. However, a 20W, 18V solar PV module was chosen for this work. The internal layout of the system's circuitry is shown in Figure 14.

The IoT –based, stand-alone, solar powered street light with vandalisation monitoring was designed and constructed. Once the system is switched on, it takes about two (2) minutes to boot. The Wi-Fi module is recognised by the router as a mini server and a UI page pops up on the computer or mobile phone at the control station can be accessed Wi-Fi.

The UI page as shown in Figure 15 shows the state of the street light, indicating whether it is “ON” or “OFF”, the state of the buzzer, whether it is “ON/OFF”, the traffic density, if it is “IDLE” or “BUSY” and the clock. The last parameter on the first page is “configuration” which pops another page when activated. It is a dynamic system in that it updates the different parameters on the UI as they occur in real time. Each street light is assigned a certain IP address by the wireless router, and this distinguishes the lights from each other. This is necessary in order to be able to identify the particular street light where there is activity, or that is faulty and needs attention.

The Arduino Wi-Fi module, being the brain of the system, is programmed to turn on the street light by 6pm. It is assumed that by 6pm, the LDR would have sensed enough darkness to send a low input voltage signal to the analog pin of the Wi-Fi module. The LED array will come “ON” with full brightness till 11pm. Again, it is assumed that the traffic density is reduced from 11pm, therefore the LED array switches to the “DIM” state. At this moment, only one of the indicators on the IR sensor (car-sense) blinks, indicating that the IR sensor module is powered.

However, when the IR (car-sense) senses movement of a vehicle, it sends a signal to the Wi-Fi module to switch the light to its full bright state and maintain the “BRIGHT” state for two (2) minutes before switching back to the “DIM” state. Overall, the design and construction of this study was successful and the system functioned as designed. The implemented system with its features is as shown in Figure 16.

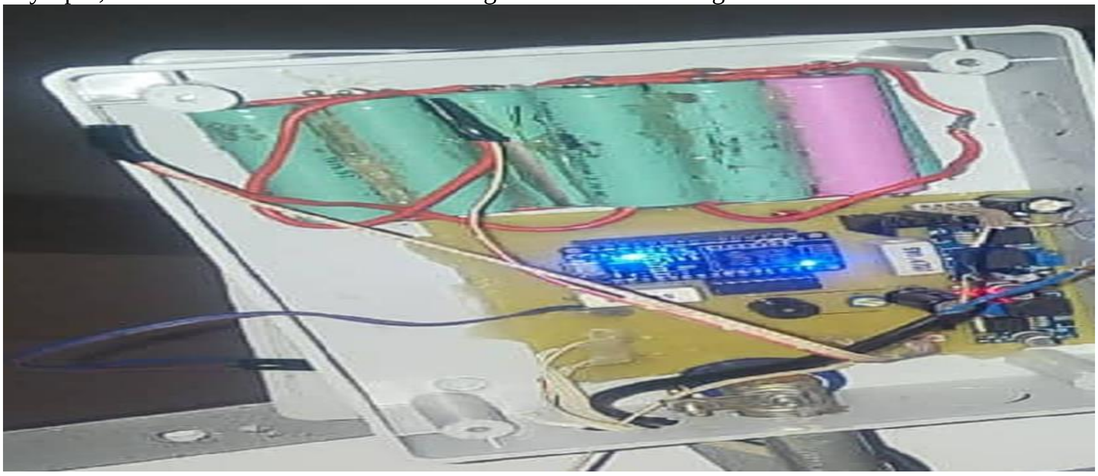

Figure 14. The internal layout of the system

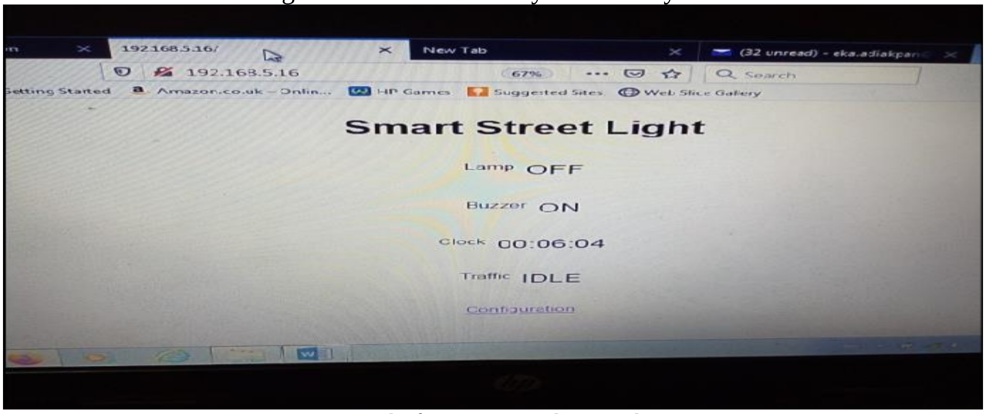

Figure 15. The first UI page at the control station

Figure 16. The implemented stand-alone street light

IV. CONCLUSION

Details on the design and construction of the circuits for an IoT-based, stand-alone, solar powered street light with vandalisation monitoring and tracking mechanism is presented. The circuit diagrams and along with careful calculations to determine the value of the various components of the circuits are also presented. The system is designed to ethane energy saving functionality by adopting lithium batteries which have faster charging rate and better energy density than its lead-acid counterparts. Additionally, the system also achieves energy saving by its intelligence section which controls the dimming or brightening of the lights as at when required. The system also employed motion sensors that manage the power consumption of the street light to a minimal level by monitoring movements thereby providing light intensity sufficient for the occasion. After implementation, the system was tested and the test results showed that the implemented IoT-based stand-alone street lights worked according to design. The need for manual control of the street light is eliminated in this work by employing the LDR which automatically turns ON/OFF the street lights. Ultimately, by utilizing the Wi-Fi network for remote monitoring of the system operation and location, and through a compact size and the vandalisation monitoring mechanism in place, the problem of vandalisation is addressed. In future, the system can be expanded to perform additional functions that may include the following;

i) Counting of the number of vehicles on the road on a daily basis.

ii) Determine the density traffic

iii) Monitor and communicate weather conditions to road users by employing the LDR and IoT.

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