

Design and Implementation of an IoT-Enabled Autonomous Night-Vision Patrolling Robot using Raspberry Pi

Yerrarapu Sravani Devi, Assistant Professor, Computer Science and Engineering, GITAM School of Computer Science and Systems Engineering, GITAM Deemed to be University, Hyderabad, India.

syerrara@gitam.edu

Meeniga Vijaya Lakshmi, Department of Electronics and Communications Engineering, G.Narayanamma Institute of Technology and Science, Hyderabad, India

m.vijayalakshmi@gnits.ac.in

Swapna Raghunath, Department of Electronics and Communications Engineering, G.Narayanamma Institute of Technology and Science, Hyderabad, India

swapna.raghunath@gnits.ac.in

K. Syamala Devi, Department of Basic Sciences, G.Narayanamma Institute of Technology and Science, Hyderabad, India

syamaladevi@gnits.ac.in

Bestha Venkateshulu, Department of Electronics and Communications Engineering, G.Narayanamma Institute of Technology and Science, Hyderabad, India

b.venkateshulu@gnits.ac.in

Markapuram Aparna, Department of Humanities and Mathematics, G.Narayanamma Institute of Technology and Science, Hyderabad, India

maparna@gnits.ac.in

ABSTRACT

For night-time surveillance of restricted premises such as residential, institutional, industrial and other restricted premises, it is required to ensure the continuous monitoring of the premises but in a manner that minimizes human contact with potentially hazardous situations. In this paper, design and implementation of an autonomous patrolling robot for real-time night time surveillance by using Raspberry Pi is presented. The system proposed consists of a night-vision camera, sound sensor, infrared (IR) sensors, GPS module, wireless communication and a mobile platform that moves by means of a motor. The robot carries out a preprogrammed patrol pattern and reacts to detecting a sound activity by turning the camera on to take images of the environment. The IR sensor is used for obstacle detection for collision avoidance and the night vision camera can be used for visual monitoring during low light conditions. Images from the robot are captured and then radioed to a web-based monitoring interface so that the robot may be observed and manually controlled, if necessary, via the wireless network. The prototype illustrates the viability of integrating mobile robotics, embedded computing, night vision imaging and remote monitoring using IoT into a portable surveillance system that is low-cost. The proposed system can be easily modified for applications, such as security patrol, hazardous area inspection, search and rescue, and others that demand continuous remote surveillance.

Keywords

Autonomous Surveillance, Patrolling Robot, Night Vision, Raspberry Pi, Internet of Things (IoT), Obstacle Detection, GPS Tracking, Remote Monitoring

1. INTRODUCTION

Safety and security have become a growing concern for residential, institutional, industrial, commercial and infrastructure applications especially if there is a need for constant monitoring at night and low visibility areas. Violence and unsafe environments around the world remain a large social and economic burden. Injuries are the cause of about 4.4 million deaths annually, with about 1.25 million of these deaths related to violence, according to the World Health Organization (WHO) [1]. In 2021 the United Nations Office on Drugs and Crime (UNODC) estimated that some 458,000 people were killed intentionally throughout the world, which is about 52 deaths per hour on average [2]. These figures do not directly reflect the number of incidents relating to surveillance, but do reveal the ongoing need for sound methods and tools to be able to detect, monitor and respond swiftly to potentially unsafe situations. It is even more relevant when applied in the night-time, where the lack of illumination, few people around and tiredness by the long period of surveillance can impact the effectiveness of traditional security measures.

Most of the traditional surveillance systems rely on stationary cameras and human security officers. Fixed cameras offer a continuous visual monitoring, but are limited by camera location and field of view [3], [4]. Many areas may need to be covered by many cameras, or by cameras that are out of range of the camera's field of view. Human based patrolling offers mobility, but requires regular operational effort and places personnel in potential risky or isolated situations [5]. As a result, mobile robotic platforms have become an alternative, or complementary, solution in which sensing, mobility, communication and surveillance capabilities can be combined in one. With the ease of access of embedded computing platforms and wireless communication systems, the possibility of low-cost mobile robots to acquire environmental information and send it to remote users in near real-time is more and more becoming possible [6], [7].

Recent study has shown that there have been major advances in robotic surveillance. Gadekar et al. designed a semi-autonomous surveillance robot with a Raspberry Pi computer, infrared sensors, video capturing, obstacle avoidance and remote video streaming [8]. The system was, however, not particularly targeted to a strategy of integrated night patrolling, but was mainly developed as a semi-autonomous platform. To solve this problem, multiple robots may be employed to cover a specific target area and coordinate their motion, Noh et al. introduced a multi-agent scheduling framework for intelligent surveillance (MASS), which focused on covering-oriented path planning and allocation of patrol paths among multiple robots [9]. While the method is concerned with a systematic approach to area coverage, for low-cost single robot deployment a much simpler multi-robot planning framework is required.

Meddeb et al. designed an IoT communication-based surveillance robot using Raspberry Pi 4 micro-computer, camera, PIR sensor and Haar Cascade and Local Binary Pattern Histogram (LBPH) face recognition methods [10]. The system is able to monitor and identify unknown individuals remotely, however due to its reliance on facial recognition the system's accuracy of surveillance is dependent on image quality, visibility, and successful detection of a face. Joy et al. created a smart security patrol robot using a Raspberry Pi microcomputer, which is equipped with a camera, sound sensor, GPS receiver and wireless communication system [11]. The system is especially pertinent to the current project as it illustrates video surveillance and video and location transmission using sound as a cue. However, the work does not focus on a particular night-vision surveillance system setup that incorporates obstacle detection and continuous predefined-routing patrolling.

Bale et al. have suggested a computer-vision-based smart patrolling robot for detecting intruder and avoiding obstacles, using a UP Squared board and OpenCV [12]. Computer vision offers greater perception capabilities, but if a more powerful and computation-intensive platform is used, the system is more complex than a low computational system like a Raspberry Pi-based system. Sathish et al., created an autonomous surveillance robot, DRISHTI, for indoor environments by utilizing ROS, simultaneous localization and mapping (SLAM) using Cartographer, facial recognition, human tracking and intrusion alarm panel [13]. The system is capable of advanced autonomous navigation but, if the environment is structured, the use of SLAM and ROS is not mandatory and requires extra computational and implementation work for a predefined patrol route is enough to operate the system.

Islam et al. designed an autonomous surveillance robot based on Raspberry Pi containing obstacle avoidance, conventional camera, night-vision camera, object detection and wireless monitoring known as the Night-Guard 360 Sentinel [14]. The work illustrates the power of using night vision with a robotic system with autonomy. It has machine learning-based architecture to detect intruders and more advanced autonomous navigation, which makes it more complex and difficult to compute and implement. Soler et al. suggested an autonomous security robot which combines environment mapping, computer vision, threat detection, web-based reporting and remote control [15]. These systems offer more context and decision-making power but are relatively more complex for cost-constrained surveillance systems because of the need to map and the power needed to process the computer vision.

In recent years, Pham and Mai have presented an IoT-based mobile robot for home security, which combines intrusion detection sensors and a camera to monitor remotely the home and to notify users immediately in case of intrusion [16]. The study shows that mobility and IoT communication are useful for certain applications but mainly those concerning home security rather than night time patrolling. Likewise, Meem et al. proposed an autonomous mobile surveillance system based on low-costs night vision camera and IoT technologies [17]. The developments show how vital mobile night surveillance is, as well as a potential for a simpler architecture that features mobility, night vision, event triggered sensing, obstacle avoidance, localisation and remote monitoring and control, without the heavy use of computer intensive artificial intelligence methods.

Observations indicate that a surveillance platform that is mobile, low cost, night capable, remotely accessible and can respond to events in the environment with safe navigation is needed. The proposed IoT-Enabled Autonomous Night-Vision Patrolling Robot fulfils this requirement by using its integrated architecture based on the Raspberry Pi. The robot moves in a designated path, and detects abnormal sound behaviour with the sound sensor. If a sound is detected, the night-vision camera is turned on and can see what is going on around. IR sensors allow obstacles to be detected and the robot can change its path to decrease the risk for collision [18], [19]. A GPS module gives an indication of location and Wi-Fi IoT communication is used to relay captured information to a remote monitoring interface [20]. The user may watch captured images, check the location of the robot, check surveillance activity and manually control the robot, if necessary, by using a web interface.

The importance of the proposed system is that all the above-mentioned functions are combined in a fairly simple embedded architecture with the ability of event-based sensing, night-vision imaging, mobile patrolling, obstacle avoidance, GPS localization, and IoT

based, remote monitoring. The system is not intended to replace the high-end surveillance systems with advanced AI algorithms, but rather to complement institutions that can be structured to allow for the regular movement of a restricted number of people along a predetermined course and provide a timely transmission of the visual information. The architecture that emerges in the result is very practical when it comes to building security monitoring in certain areas, such as buildings, institutional property, warehouses, restricted areas, hazardous environments, or anywhere else that needs to be monitored periodically or continuously. The prototype that was created in this work illustrates how easy it is to integrate ubiquitous hardware and IoT technologies in order to minimize the need for constant human patrolling while simultaneously maintaining remote situational awareness.

2. METHODOLOGY

The IoT-Enabled Autonomous Night-Vision Patrolling Robot is designed to be a mobile monitoring station that can continuously monitor a predefined area, such as at night and in low light conditions [21]. It consists of an embedded Raspberry Pi controller, a night-vision camera, sound sensor, infrared (IR) obstacle sensors, GPS module, wireless communication and a motor-driven mobile platform. The methodology includes system architecture, embedded control, environmental sensing, mobile navigation, night-vision surveillance, location tracking, and IoT communication remotely.

2.1 System Architecture

Simplified block diagram of the proposed patrolling robot is shown in Fig.1. The Raspberry Pi is the main processor/commander and communicates with all the sensing, imaging, communication and actuation modules. All major subsystems consist of a night-vision camera, sound sensor, two IR sensors, GPS module, a Wi-Fi communication, a motor driver, and finally, DC motors.

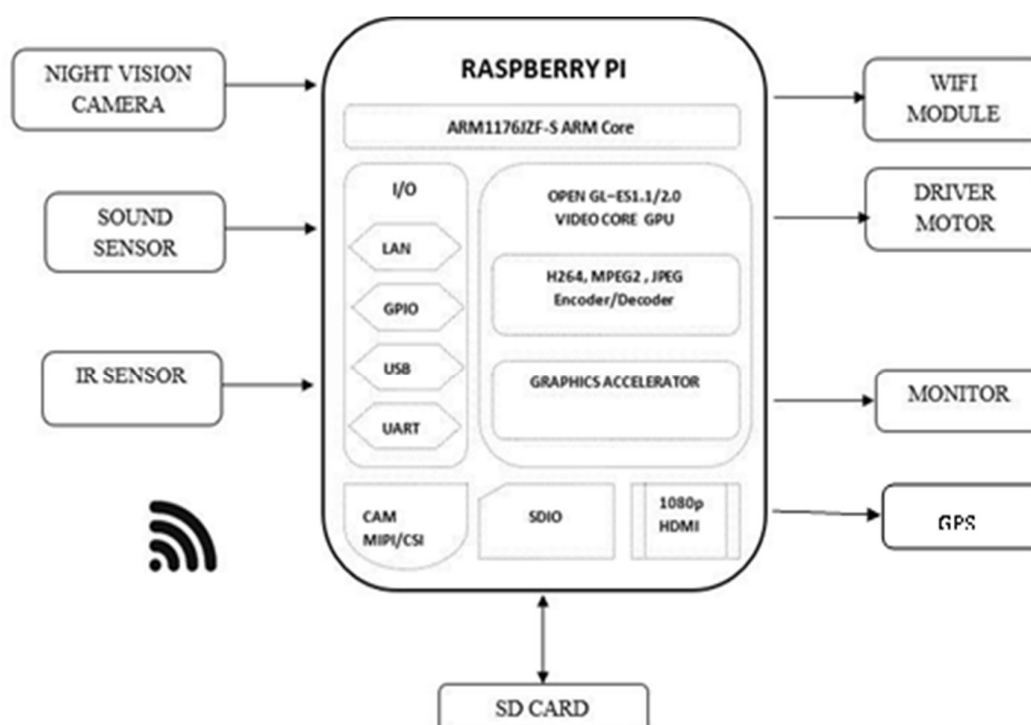


Fig. 1. Overall block diagram of the proposed IoT-enabled autonomous night-vision patrolling robot

A surveillance area is explicitly defined and the robot takes actions there. The Raspberry Pi receives data from the environment sensors and sends the data to the control commands during routine patrolling. The IR sensors can detect obstacles and the sound sensor can detect important sounds in the environment. If a sound comes from an event, the night vision camera is enabled to take a picture of the scene around the event. The collected data and GPS location is sent wirelessly via a network to a remote monitoring interface.

2.2 Embedded Control Unit

The proposed system is based on Raspberry Pi 3 Model B+ as the central controller. It offers the necessary number of processing resources and GPIO pads to connect the sensors/actuators. The pin configuration for the Raspberry Pi with different components of the system is shown in Fig. 2. The Raspberry Pi runs a Linux based operating system, and runs the control program written in Python. It is used to control the acquisition of data from sensors, the control of motors, the operation of the camera and the wireless communication. Embedded controller is thus the link between the actual sensing and actuation components and the remote monitoring application.

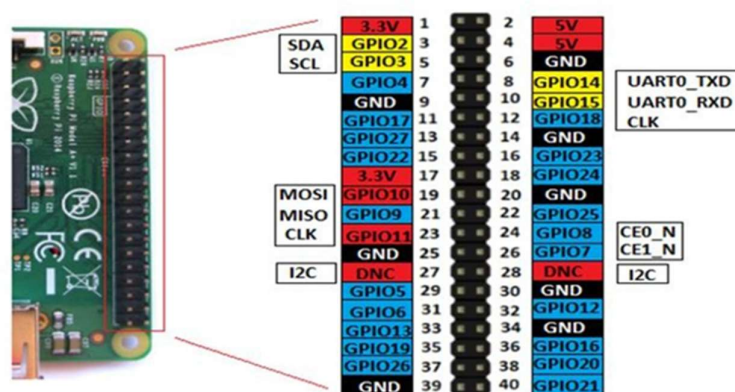


Fig. 2. Raspberry Pi 3 Model B+ pin configuration

2.3 Environmental Sensing

The IR sensors and sound sensor are used to carry out environmental monitoring. IR sensors are mainly employed to sense obstacles that are in the robot's way. The working principle of IR sensor is presented in Fig. 3. The IR LED is directed towards the surrounding area and the reflected radiation is received by the photodiode. When the received signal changes, it means that there is an object in the sensing range.

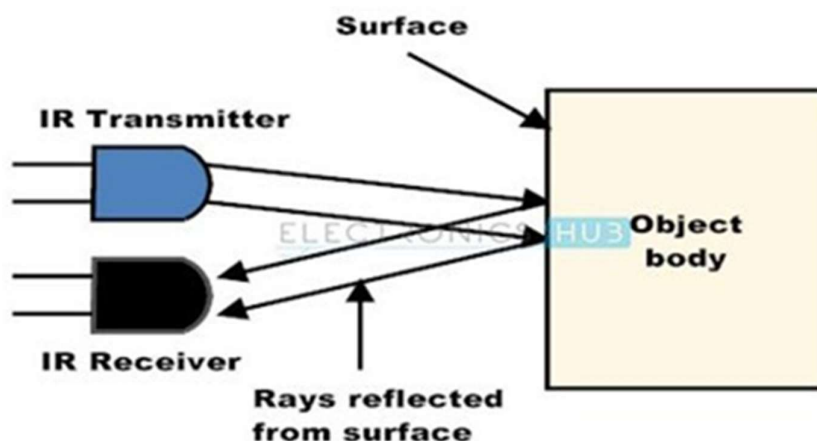


Fig. 3. The principle of operation of an infrared obstacle-detection sensor

The circuit diagram of the obstacle sensing circuit used in the prototype is presented in Fig. 4. The robot has two IR sensors to detect any obstacles that are on the side of its movement path. The output signals from the sensors are sent to the Raspberry Pi which processes the signals and triggers the appropriate movements. In the event of an obstacle blocking the robot, the robot turns around, to avoid the obstacle, and then resumes the programmed patrol path again.

The other sensing method is a sound sensor which is basically an LM393. The sensor will output a digital signal if the sound level detected is above the set level. The potentiometer on the board can be used to adjust the threshold. During patrolling, the output of the sensor is continually monitored by the Raspberry Pi. Any sound event that exceeds the set threshold is considered as a trigger for visual surveillance.

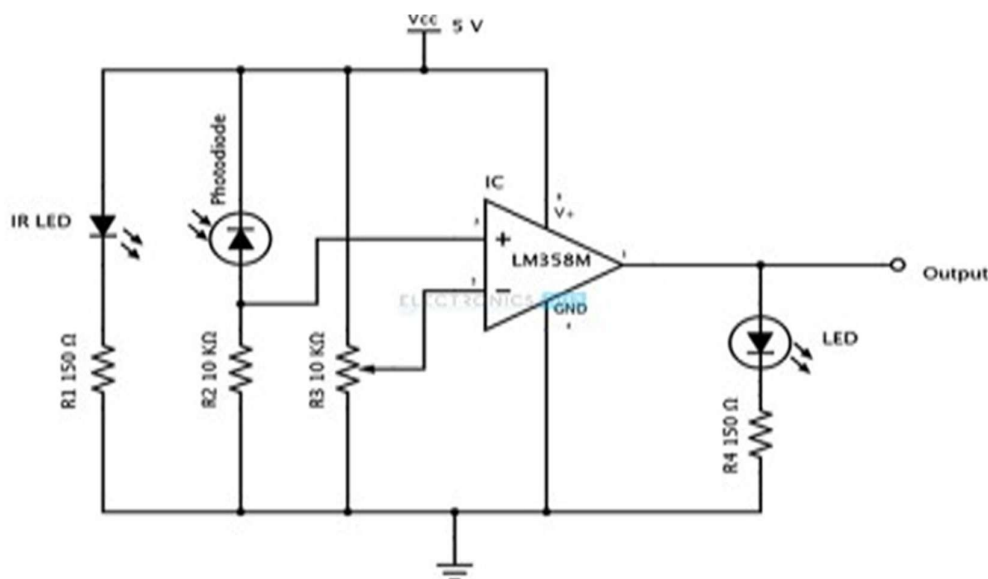


Fig. 4. IR-based obstacle-detection circuit

2.4 Mobile Platform and Autonomous Patrolling.

A wheeled chassis with two motor driven wheels and two free wheels is used to build the robot. The propulsion and direction of the wheels are given by the motor-driven wheels, and mechanical support is offered by the free wheels. To supply the motors with the correct amount of current and to keep the motor load away from the controller, the motor current is

provided by a motor driver module in between the Raspberry Pi and the motors. The robot runs an already defined patrol path, programmed into the Raspberry Pi. This is an option for premises with a predetermined path and a structure. The IR sensors are constantly scanning the nearby environment while the robot is in motion. If a robot encounters an obstacle, the controller outputs a direction command to modify the direction of the robot, and avoid the obstacle.

2.5 Night-Vision Surveillance

The Pi camera is enhanced with a night-vision mode, which is implemented on the Raspberry Pi. The proposed system's primary visual sensing function is fulfilled by the camera. Can be angled towards the surrounding area to get a broader overview of the area being monitored. The camera function is coupled with the mechanism for detecting the sound. The sound sensor is always turned on when not in use during normal patrolling, and constantly monitors the surrounding environment. The Raspberry Pi starts the image-acquisition process when an acoustic event is larger than a set threshold. The camera then takes a picture of the surrounding scene that is then observed by the remote user. This approach will utilize acoustic sensing and night-vision imaging in the same manner, such that the system will react to potentially important environmental events in addition to performing the normal mobile surveillance.

2.6 GPS-Based Localization

The robotic platform is equipped with a GPS module to get the geographic location of the platform. The GPS receiver gives latitude and longitude data, and the Raspberry Pi during its operation gets the data. The location information is linked to the robot's surveillance activity, and sent to the remote user via a wireless communications network. This allows the operator to estimate the location of the robot if he/she is remote from the system. GPS based localization is advantageous especially when the robot is used over a larger premises, where the operator wants to know the current location of the mobile surveillance unit.

Mobile robot and remote monitoring unit are connected by wireless communication. Python, HTML and JavaScript are used to implement the IoT application. The Raspberry Pi is used as local processing and communication unit, and the web-based interface is used to give a user access to surveillance information. The communication architecture allows the acquired images and GPS data to be sent from the robot to the remote monitoring interface. Accordingly, the user may watch the data about the surveillance remotely, without being physically near the robot. The system can be controlled remotely via the web interface, as well as operated autonomously. The Raspberry Pi takes the user's control instructions and translates them into the correct signals for controlling the motors. Therefore, the proposed system is integrated with autonomous patrolling and human participation in case of need.

2.7 Integrated System Operation

The proposed IoT-Enabled Autonomous Night-Vision Patrolling Robot is proposed to be a single robot that carries all sensing, navigation, imaging, localization and communication required for a single round of night vision patrolling. First, the Raspberry Pi starts up the built-in sensors, camera, GPS module, motor driver and wireless communication interface. The robot then starts to move on the preprogrammed patrol path. On movement, the IR sensor continuously scans for obstacles. If such an obstacle is detected, the controller will change the direction of the robot so that it does not collide and will continue the patrol sequence.

At the same time, the sound sensor is measuring the surrounding. If the sound that's being picked up is louder than what's been set, the Raspberry Pi activates night vision camera to take a photo of the environment. The corresponding geographical location is provided by the GPS module and the wireless communication interface transmits the information available for surveillance to the remote monitoring system.

The proposed approach encompasses all these functions in a mobile platform based on a Raspberry Pi micro-computer. This leads to a relatively inexpensive and straightforward way to monitor your property at night when you're away and less responsibility on the physical security personnel to do continuous patrolling. The programmed-path method also enables the system to be adapted to a structured and relatively flat facility where it is possible to define a set path to cover the surveillance area.

3. RESULTS AND DISCUSSION

All the components of the developed IoT-Enabled Autonomous Night-Vision Patrolling Robot were assembled and integrated with the Raspberry Pi controller, mobile platform driven by a motor, IR obstacle sensors, sound sensor, night-vision camera, GPS module, wireless communication unit and power supply. The physical integration, patrolling operation, environmental sensing, night vision surveillance, remote monitoring, and location tracking were among the aspects that were primarily considered in the evaluation of the prototype. The results show that it is possible to implement a compact embedded platform to carry a mobile surveillance system in a predetermined and relatively flat environment.

The robot designed is presented in Fig. 5. The wheeled platform is a necessary mobility facilitating the movement on the predefined surveillance route. Two motor driven wheels coupled with two free wheels present a relatively simple mechanical setup, while cutting the number of motors (and therefore power requirement) in use. The compact design also enables the integration of the sensing, computing, imaging and communication modules on a single mobile platform. In Fig. 6, the major components on the chassis are shown in their arrangement. All the Raspberry Pi, IR sensors, sound sensor, night-vision camera, motor driver, DC motors, storage and power supply are packaged into the robotic platform. The physical integration shows the proposed architecture is feasible to achieve with commercially available embedded components without the need for a complex robotic infrastructure.



Fig. 5. The front view of the developed autonomous patrolling robot with night vision enhanced by IoT technology.

The prototype has the characteristics of being suitable for controlled areas like institutional buildings, warehouses, industrial areas, restricted premises, and other sites that can set up a defined patrol path. This can help to decrease the amount of time that needs to be spent on physical patrolling, and can also enable surveillance in areas that may be difficult or unsafe to have humans present for a long period of time. This is a wheeled configuration, but restricts the robot mostly to relatively smooth and flat surfaces. It does not therefore perform well on rocky, uneven or slopes.

3.2 Autonomous Patrolling and Obstacle Avoidance

After the system was initialized, a program was written for the robot to follow a certain path. The motor-driver interface was used to control the movement of the Raspberry Pi. The robot could perform the programmed patrol sequence without having to continuously send the robot move commands. The movement process was modified by using the two IR sensors to include obstacle detection. If an obstacle was detected, the output of the sensor was sent to the Raspberry Pi, which then would emit a directionally-based response to prevent the obstacle. This gives it a basic reactive navigation ability, and can be used especially in a structured environment where the robot is not needed to build a map or to locate itself autonomously.

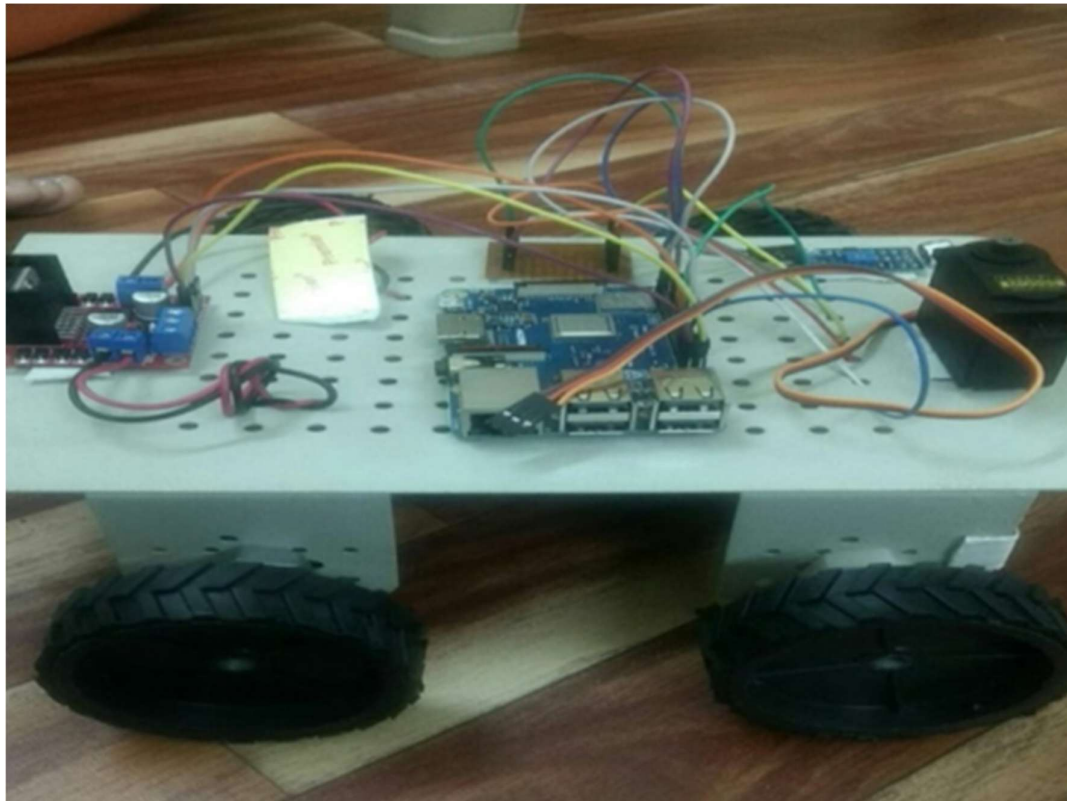


Fig. 6. The components attached to the robot's chassis

The obstacle-detection mechanism is important for the unattended operation as the mobile surveillance robot would have to be frequently interfered by human in operation without such mechanism. The proposed system will enable the robot to resume its patrol following a direction change due to an obstacle. However, the current one is a reactive motion for avoiding obstacles and not intelligent path planning. It does not build an environmental map or find an optimal choice of alternative path. This is a significant area of improvement that needs to be developed in the future.

3.3 Sound-Triggered Surveillance

For the patrol operation, an event triggering mechanism was used, based on the sound sensor. The Raspberry Pi started the visual surveillance process when the sound was detected, and was above the set threshold. This sets an interesting link between camera operation and environmental sensing: the robot is not required to rely solely on visual information from a continuous camera but can react to an acoustic event by switching the attention to the region around it. The sound activated mechanism is especially beneficial in night time surveillance, in which the range is decreased and a concealed noise could be a first warning sign of activity in the monitored area. Therefore, it can be used in areas like storage areas, industrial areas, isolated areas, and restricted areas where the unexpected movement or activity is required to be investigated.

The sound sensor in the prototype is based on a threshold, which does not judge the sound source. The surveillance response may therefore also be caused by 'environmental' noise. The current system should therefore be considered a surveillance system with a trigger mechanism for events instead of an intelligent classification system using acoustics.

3.4 Night-Vision Image Acquisition

The night-vision camera provides the principal visual surveillance capability of the robot. Once the surveillance process is triggered, images of the surrounding area are captured and made available to the remote monitoring system. Representative images obtained from the developed system are shown in Fig. 7.

The captured images demonstrate the ability of the mobile platform to obtain visual information from its surroundings rather than relying on fixed surveillance cameras. This mobility provides an important advantage because the camera can be physically transported to different locations along the patrol route. The night-vision capability further extends the usefulness of the platform to low-light and night-time environments. The captured images can also provide visual information to a remote operator for subsequent assessment. However, the current prototype does not perform automatic classification or identification of people or objects in the captured images. Therefore, interpretation of the acquired visual information remains dependent on the remote user. Incorporating object detection, human detection, or face recognition in future versions could provide a higher level of automated surveillance.

3.5 IoT-Based Remote Monitoring

The captured surveillance information was transmitted through the wireless network to a web-based monitoring interface. The developed interface enables the remote user to access the information generated by the robot without being physically located at the patrol site. This establishes the IoT component of the proposed system and provides an important advantage over a standalone mobile robot. The web-based monitoring interface developed using Python, HTML, and JavaScript provides access to the captured images and GPS information. The interface also supports remote movement control when manual intervention is required. Thus, the proposed system combines autonomous operation with supervisory human control, rather than requiring the robot to operate completely independently under all circumstances.

This hybrid mode is advantageous for security applications because the robot can perform routine patrolling autonomously while the operator can intervene when an event requires closer inspection or a change in movement. This will help to lessen the sustained vigilant effort (SVE) required from security staff members, while maintaining human judgment.

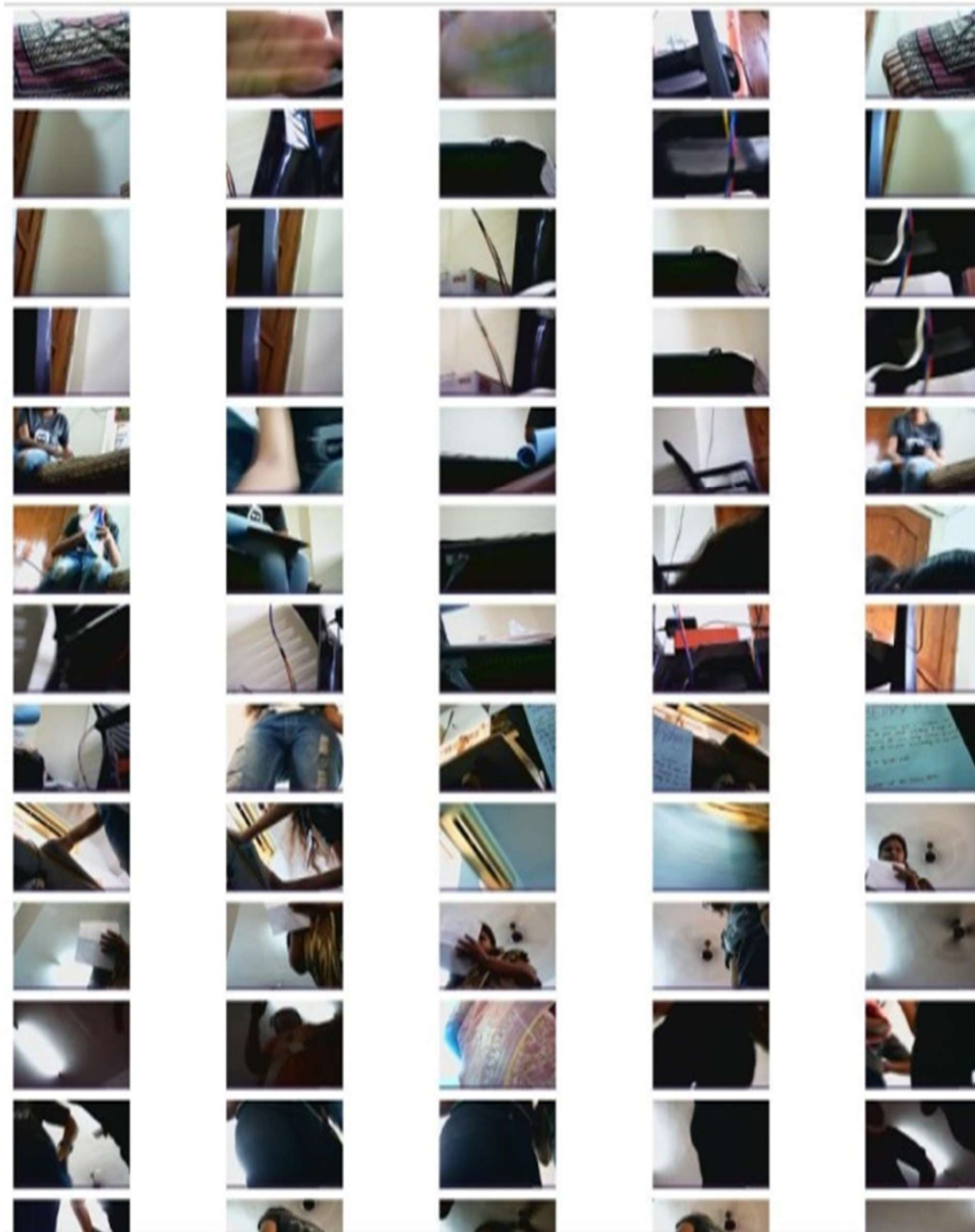


Fig. 7. Representative night-vision images captured by the patrolling robot

3.6 GPS-Based Location Tracking

The GPS module supplies the geographical location of the robot during the robot's operation. The monitoring interface displayed via the web allows the location of the GPS receiver in terms of latitude and longitude to be displayed, as is evident in Fig. 8.

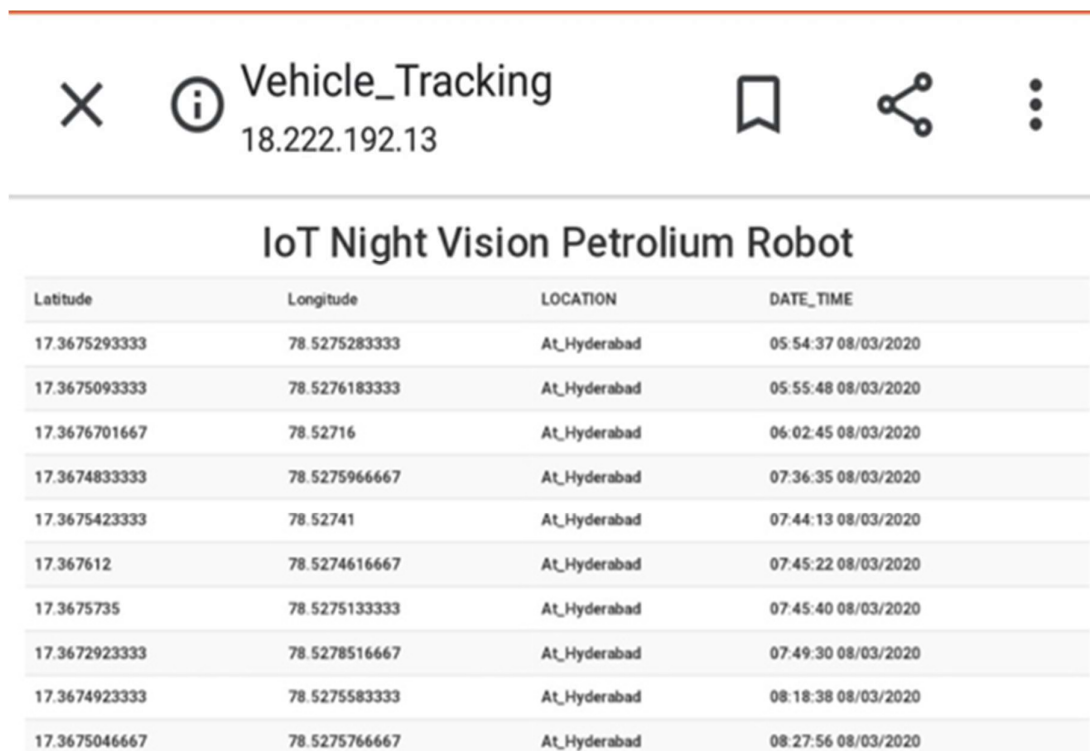


Fig. 8. The monitoring interface showing the Latitude and Longitude data from GPS.

The use of location information together with surveillance images adds more context to remote monitoring. If the event happens, the operator can roughly determine where the robot is and link the visual information that is taken at that time to the position of the robot. This is important when the robot is used over a relatively large premises where location of the robot may be difficult to obtain, traditionally, by manual means. GPS tracking further improves the real-world usability for the system in security patrol and inspection. The effectiveness of GPS, though, relies on the availability and quality of the GPS satellites' signals, and more localization means might still be necessary when the GPS signal is unavailable or weak in enclosed spaces or in GPS denied areas.

3.7 Integrated Surveillance Operation

The integration of the different subsystems has been accomplished, and a complete surveillance sequence was built up. The robot will operate and follow its set path while sensing its environment. IR sensors detect obstacles, acoustic sensor detects sound events, night vision camera provides visual information, GPS module provides location information and the wireless interface makes the collected information available to the remote user. Captured image can also be linked with Date and Time Information.

One of the key features of the proposed system is its ability to incorporate these functions. Sensors and communication modules do not work as standalone sensing devices but rather together in the surveillance process. Image acquisition can be triggered by an acoustic event, the robot location can be correlated to the surveillance event and data can be remotely retrieved. This yields a simple event-to-information chain from sensing the environment to remote situational awareness. The prototype shows that it is possible to achieve mobile remote surveillance of night time using a low-cost platform based on a Raspberry Pi. The robot's mobility will enable the areas to be periodically checked without the installation of a

large number of fixed cameras, whereas, the night vision camera will allow for surveillance in low light conditions. The remote access also enables the security operator to keep abreast of the robot's operations from a control site and not have to follow the robot all the time.

The proposed system can therefore be applicable for systems such as institutional and industrial premises, warehouses, restricted areas, hazardous-area inspection, defence and security support and search-and-rescue operations where it is advantageous to be able to move around and observe visually. A remotely monitored Robotic Platform may allow further reduction in the need for personnel to enter an area for preliminary inspection, in hazardous environments.

Meanwhile, there are some drawbacks to the prototype. It has a preprogrammed path through which the robot can navigate which can only be used in environments where the path is known. The IR-based obstacle avoidance is only local reactive navigation and the sound sensor will not differentiate between useful sounds and unwanted sounds and will just respond if the sound level is exceeded. Wireless connectivity is also essential for the system's ability to monitor remotely, while having enough power to run it for long periods of time. Moreover, the present prototype does not contain automated human or object recognition, intelligent threat classification or advanced autonomous path planning.

In general, it can be seen that the experimental prototype shows the possibility of implementing a mobile patrolling system, obstacle sensing, a system that activates surveillance sound, imaging at night, GPS tracking and web-based remote monitoring all on a single embedded system that is the IoT-Enabled Autonomous Night-Vision Patrolling Robot (IoT-ANAP). The findings confirm the practicality of the suggested architecture for the structured environment as a tool for surveillance. It has a relatively simple hardware and software structure, and can be used as a platform for subsequent development of more "intelligent" robotic surveillance systems.

CONCLUSIONS AND FUTURE SCOPE

This paper introduced to the reader the design and implementation of an IoT-Enabled Autonomous Night-Vision Patrolling Robot (IoT-ANAP), based on using the Raspberry Pi. The prototype incorporates the predefined path navigation, sound triggered image acquisition, IR obstacle detection, night vision imaging, GPS location tracking and web based remote monitoring and control. The prototype system presented here shows that the functions are possible to be integrated in a relatively simple, cost-effective mobile surveillance platform. It is mobile, and can be accessed remotely which makes it potentially useful in institutional premises, warehouses, industrial premises and other structured spaces that need periodic checks. This is however limited to the ability to detect sounds exceeding a threshold, the reactive avoidance of obstacles, the need to follow a pre-defined path, wireless connectivity, and lack of automated human or object recognition.

Future efforts involve integrating with intelligent sound classification, and human and object detection using computer vision to enhance event identification and minimize false alarms. Advanced navigation techniques (for example, simultaneous localization and mapping (SLAM)) could allow operation in environments that are not familiar and improved localization techniques could allow operation in GPS denied indoor spaces. Additionally, performance in varying lighting and environmental conditions, along with the reliability of wireless communications should be explored. The performance of the system in obstacle detection, sound-trigger response, image-transmission delay, and patrol reliability could be

quantitatively evaluated, which would be helpful to verify the effectiveness and practicality of the deployment of the system.

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