Design and development of a quadruped home surveillance robot

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ABSTRACT

Quadruped home surveillance robots represent a promising advancement in home security and automation. This innovative robotic system is equipped with four-legged locomotion, allowing it to traverse various terrains within a household environment. The robot's primary function is surveillance, and it is equipped with high-definition cameras, motion sensors, and object recognition software. These sensors enable the robot to detect intruders, track their movements, and capture real-time video footage for remote monitoring. The quadruped robot's compact and agile design allows it to navigate through narrow spaces and overcome obstacles, ensuring it can patrol every corner of a home effectively. Its autonomous operation is made possible through advanced artificial intelligence algorithms, ensuring that it can detect anomalies and respond to security threats promptly. Furthermore, integrating the robot with smart home systems enables seamless communication with other connected devices and allows homeowners to control and monitor it remotely.

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1. INTRODUCTION

The Robot Institute of America described a robot as a multifunctional, reprogrammable manipulator that can move materials, parts, tools, or specialized equipment through a range of programmed motions to accomplish several tasks [1]. A robot is an autonomous device that can sense its surroundings, process information to make decisions, and act in the real world. It can also be described as a kind of automated device that can quickly and precisely carry out particular activities with little or no assistance from humans [2].

Robots are generally classified into two categories, namely, locomotion and application. The application-specific robots are industrial robots and service robots. Industrial robots are robots that are used for manufacturing and the logistics of materials in the manufacturing process [3]. Service robots are defined by the International Organization for Standards as robots for personal or professional use that perform useful tasks in different environments [4]. Additionally, robots can be classified based on their locomotion, which refers to the method by which they move in different environments. They could either be stationary or mobile robots. Stationary robots are robots that conduct tasks in a set location and are not mobile in any way [5]. Mobile robots are robots that can move around their environment. These robots are heavily structured by software programming and use sensors and other technologies, such as artificial intelligence, to identify and move around their environment [6]. Robots are also classified based on locomotion, which is the method by which robots move in different environments. They could either be stationary or mobile robots. Stationary robots are robots that conduct their tasks in a set location and are not mobile in any way [7]. Mobile robots are robots that can move around their environment. These robots are heavily structured by software programming and use sensors and other technologies, such as artificial intelligence (AI), to identify their environment [8].

Home invasion has emerged as a major social vice all across the world. Inadequate security, poverty, substance addiction, peer group pressure, and many more factors are some of the main causes of Burglaries [9]. According to Burglary Statistics, 65% of people personally know their thieves are, and there is a very high likelihood that a friend or neighbor may try to rob you. Due to the fast-paced nature of burglary crimes and the potential difficulty for both homeowners and police to identify the perpetrator, only 13% of reported burglary cases are resolved by the police. To combat the increase in home invasions, we proposed the development of a home security robot that can warn homeowners of an attempted break-in or burglary on their property. This will aid in preventing house invasions and make it easier to identify and apprehend those responsible. The design of a four-legged robot moves around its environment, detects if there are intruders, takes a picture of the intruder, sends it, and also sends a text message to the owner. If the presence of the intruder persists, the robot will make canine sounds to alert the neighborhood. This quadrupled home security robot has several essential components that will allow for the detection of intruders and the capture of images. It is also powered by rechargeable batteries.

Legged robots are mobile robots that make use of mechanical limbs for movement. They are similar to other robots, but their locomotion methods are more complicated compared to their wheeled counterparts [10]. Quadruped robots have been around for some time now. There has been a lot of interest in mobile robots over the last three decades because they can explore complex environments, perform rescue operations, and complete tasks without the need for human intervention [11]. In 1870, the first legged robot system design was made by Chebyshev with dual-axis leg motion; it was a simple 4-link system. A researcher named Rygg developed the mechanical horse in 1893, which led to further advances in legged robotic systems. A pedal was included in this type, which was entirely mechanical. Ralph Mosher and General Electric created the Walking Tuck later in 1965. It was a massive electromechanical model that could track mechanical movements using electrical inputs [12]. Further advances in quadruped robots were made possible by the integration of biological inspiration into robotic design. Notable examples of these robots include Massachusetts Institute of Technology (MIT) Cheetah [13], Boston Dynamics Spot Mini, and Tekken [14], all of which demonstrated flawless stability and fluid gait patterns.

A low-cost quadrupedal robot has been designed by using either wholly three-dimensional (3D)-printed parts or a combination of 3D-printed parts and carbon fiber. Low-cost servo motors are used in place of hydraulics, and proportional integral derivative (PID) controlled brushless direct current (DC) motors are used to move the legs. The Stanford Pupper is a quadruped robot constructed of carbon fiber and 3D-printed parts that uses 12 high-voltage servo motors and a Raspberry Pi to regulate the gait logic. It was created by robotics students at Stanford University. The spot micro robot is another inexpensive quadruped robot that is constructed primarily from 3D-printed components and is powered by an Arduino, a node MCU, a teensy board, and a Raspberry Pi.

Efe and Ogunlere [15] developed a highly customizable and inexpensive mobile home security system by connecting sensors to an Arduino ATmega2560 microcontroller to enable communication with the signal input from the sensors. A mechanism that, upon detection of an intrusion by the passive infrared (PIR) sensor, notifies the administrator application via short message service (SMS). A smartphone application designed to communicate with the home security system was part of the system that made it possible for homeowners to safely secure their residences from their smartphones. The system developed could only detect intruders using the PIR sensor, which could be set off by anything reflecting infrared (IR) light. The system could not capture the faces of intruders.

Dhakolia *et al.* [16] designed a robot capable of operating in rough terrain for surveillance and monitoring. The methodology used included a robotic arm controlled by an ESP32 development board, an Arduino Mega serving as the robot's brain, an ultrasonic sensor for obstacle avoidance, and a night vision camera unit with a radio receiver. Aluminium was used to create the robot's body. The study concluded that a four-legged walking robot is an efficient surveillance device with a wide range of applications. Also, an internet of things (IoT)-based door security system for home automation was developed in [17]. A door lock system was built with face detection and recognition, and an email alert system was developed using a web camera that captures an image and sends it to the Raspberry Pi when motion is detected by a PIR sensor device. The system compares the captured image with the image stored in the database. If the image is in the database, the door will automatically open; otherwise, an SMS warning will be sent to the user with the aid of a global system for mobile communication (GSM) module, and the door will remain locked.

Al-Obaidi *et al.* [18] developed a wireless-controlled mobile robot with low cost and low power consumption for surveillance applications. Arduino and Raspberry Pi (low-cost open-source hardware) were used for motion control and the main processing unit, respectively. The mobile robot uses sensors to track physical events in its immediate surroundings while wirelessly communicating with a control station. Without needing to recharge its battery, the robot can operate continuously at 25 rpm for 6.5 hours.

Kim *et al.* [19] designed and developed an open-source quadruple robot using a single-board computer (SBC) with a graphical processing unit (GPU), an onboard depth sensor, and off-the-shelf quasi-direct drive actuators. Two independent single-board computers (SBCs) were primarily utilized to manage the motion control and perception tasks. Motion is managed by a Lattepanda Alpha SBC, while vision is handled by an NVidia Xavier Jetson NX SBC. RMD-X8 and RMD-X8 Pro Actuators were used. Three-cell LiPo batteries were used to power the single-board computers and the actuators, respectively. To make the frame, polylactic acid (PLA) filament was utilized. The 12.7 kg quadruped robot was designed with a front walk velocity of 1.0 m/s and an average power usage of 81.6 W, enabling steady dynamic trot-walking. Shi *et al.* [20] also designed, simulated, and constructed a quadruped robot dog as a vehicle. Investigating the kinematics and inverse kinematics solutions relying on the DH approach laid the foundation for the gait algorithm.

2. MATERIAL AND METHOD

2.1. Materials

The components used in this project development include ESP 32 board, Raspberry Pi 3A+, Raspberry Pi 5MP night vision camera, PCA9685 16 channel PWM, VL53L1X time of flight sensor, SPT5430HV-180 servo motor.

2.1.1. ESP 32 board

The ESP32 as shown in Figure 1 is a series of low-cost, low-power system-on-a-chip microcontrollers with integrated Wi-Fi and dual-mode Bluetooth [21]. It is a 36-pin microcontroller with 34 pins being general-purpose input and output pins. In this work, it was used to drive the motion of the quadruped robot by controlling the walking gait and the speed of the robot.

2.1.2. Raspberry Pi 3A+

The Raspberry Pi 3A+ [22], shown in Figure 2, is a single-board computer (SBC) developed in the United Kingdom by the Raspberry Pi foundation. It comes with an Extended 40-pin GPIO header, MIPI DSI display port, MIPI CSI camera port, 4 pole stereo output and composite video port. It has a RAM of 512 MB and a power input of 5 V/2.5 A DC via a micro-USB connector. It is the main brain of the quadruped robot responsible for making decisions and detecting humans.

Figure 1. ESP 32 DEV BOARD

Figure 2. Raspberry Pi 3A+

2.1.3. Raspberry Pi 5MP night vision camera

The Raspberry Pi's camera serial interface (CSI) port accepts a direct plug from the Raspberry Pi Camera Board. It can produce images with a clear 5-megapixel (MP) quality or record 1080p high dynamic (HD) video at 30 frames per second [23]. The board itself is ideal for portable or various uses where weight and dimension are crucial because it is small, measuring just over 3g and measuring about 25 × 24 × 9 mm, the camera is shown in Figure 3.

2.1.4. PCA9685 16 channel PWM

This board is a 12-bit pulse width modulation (PWM)/servo driver that can drive up to 16 servo motors over an inter-integrated circuit (I2C) using 2 pins. It is used to drive the 12 servo motors used as shown in Figure 4.

2.1.5. VL53L1X time of flight sensor

As shown in Figure 5, the sensor is a time-of-flight one that can measure distances up to 4 m (13 ft) at 1 mm resolution. It makes use of flight sense technology to precisely measure the amount of time it takes for infrared laser light pulses to be emitted, reach the closest body or object, and be reflected to a detector. This ensures accurate distance measurement regardless of the target's color, texture, reflectivity, and other characteristics.

2.1.6. SPT5430HV-180 servo motor

It is used to move the limb of the quadruped robot at specific angles by using the principle of servomechanism. It consists of three major parts: the controlled device, the output sensor, and the feedback system. The servo motor is interfaced with the microcontroller unit by using the three wires coming out of it. Two of the wires serve as a supply (i.e., negative and positive), and the last one is used for a signal that is sent to the microcontroller. The servo motor used is shown in Figure 6.

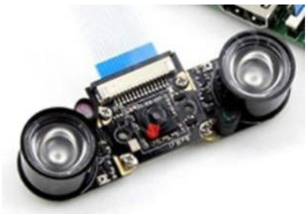

Figure 3. 5MP Raspberry Pi camera

Figure 4. PCA9685 16-channel servo driver

Figure 5. VL53L1X time of flight sensor

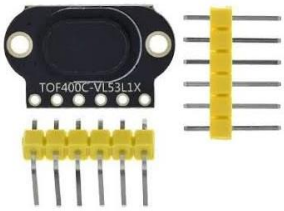

Figure 6. SPT5430HV-180 Servo motor

2.2. Method

The system consists of a microcontroller and a Raspberry Pi SBC. The Raspberry Pi acts as the main brain of the system while the ESP32 is in charge of the motion of the legs. The system is powered by either a battery of nominal voltage of 7.4 volts (i.e., a 2S battery). A 2S battery indicator is connected in parallel to the power source of the system to determine the approximate voltage range. A switch was placed to allow and cut off power to the circuit. 7.4 volts from the power source goes directly to the PCA9685 16-channel PWM driver and LM2596 dc-dc buck converter which converts the 7.4 volts to 5 volts for the ESP32 and the Raspberry Pi single board computer (SBC).

The servo motors are connected to a PCA9685 16-channel PWM driver. The right front tibia, right front femur and right front coxa servo motors are connected to PWM pins 1 to 3 respectively. The left front tibia, left front femur, and the left front coxa servo motors are connected to PWM pins 5 to 7 respectively. The left rear coxa, left rear tibia. and the left rear femur servo motors are connected to PWM pins 9 to 11 respectively. The right rear coxa, right rear tibia and the right rear femur servo motors are connected to PWM pins 13 to 14 respectively. The PCA9685 16-channel PWM driver is connected to the ESP32 board via the I2C pin, the I2C pins are the serial data (SDA) and serial clock (SCL) pin. The MPU6050 gyroscope sensor is also connected to the same I2C bus. The MPU6050 gyroscope sensor is connected to the ESP32 for stabilization of the gait. The PCA9685 16-channel PWM driver and the MPU6050 gyroscope sensors are powered by 3.3 V from the ESP32 boards.

Three VL53L1X time of Flight sensors are connected to the Raspberry Pi using an I2C pin via the TCA9548 I2C multiplexer. The VL53L1X time of flight sensors enables the robot to detect and avoid obstacles while moving. The TCA9548 I2C multiplexer and the VL53L1X time of flight sensor will be powered by 3.3 volts from the Raspberry Pi or 5 volts from an LM2596 dc-dc buck converter depending on the final current draw. An infrared camera is connected to the Raspberry Pi board to capture images. The Raspberry Pi and the ESP32 board communicate with each other using the transmit (TX) and receive (RX) pins. The circuit diagram is illustrated in Figure 7. The block diagram of all the segments is shown in

Figure 8. A printed circuit board shown in Figure 9 was designed using Altium Designer that puts the Raspberry Pi, the ESP32 board, the MPU6050 and the LM2569 AC -DC buck converter on the same board. Due to the inability to source a printed circuit board (PCB), the design was built on a double-sided 9 cm × 15 cm Vero board.

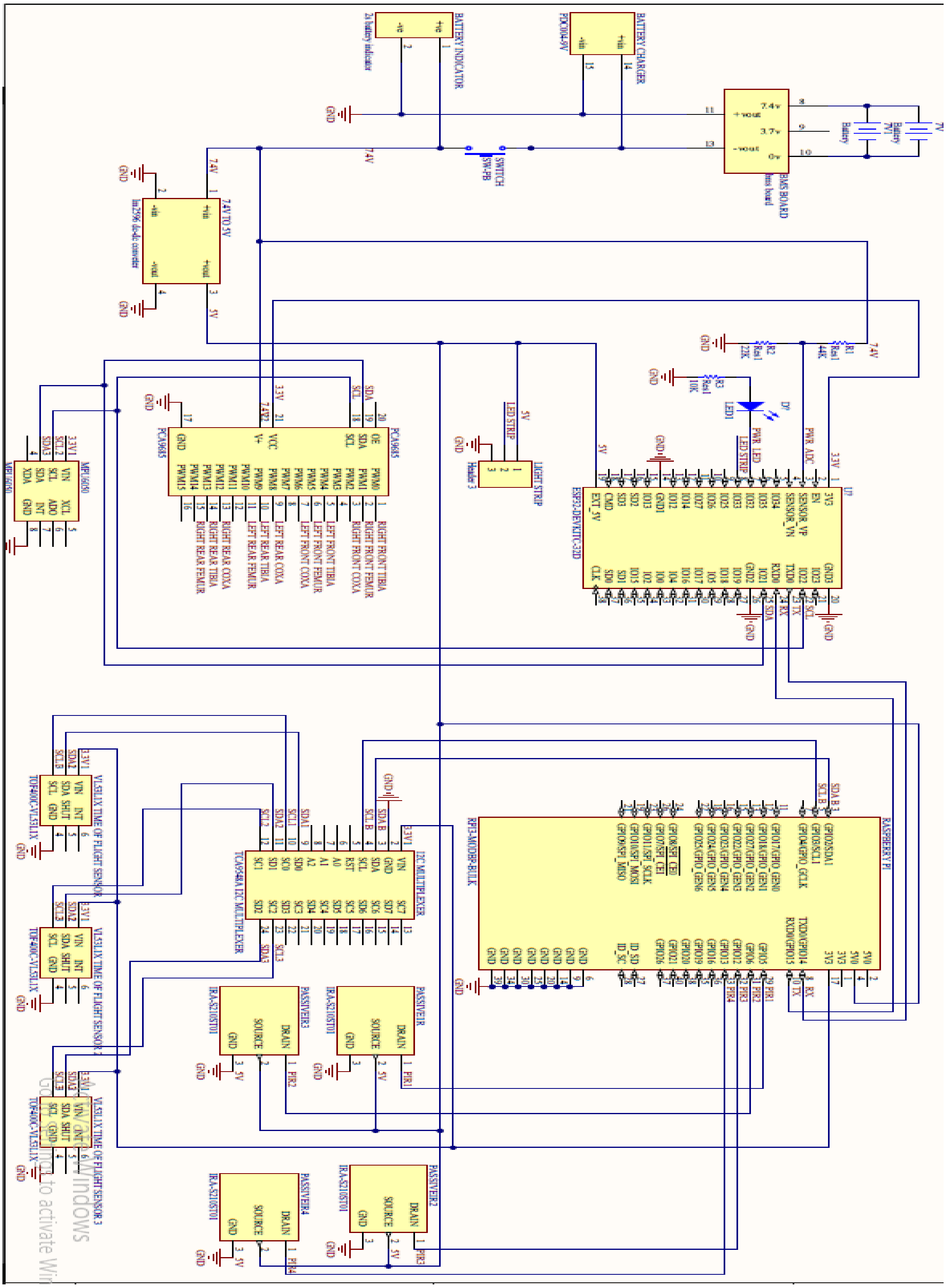

Figure 7. Circuit diagram

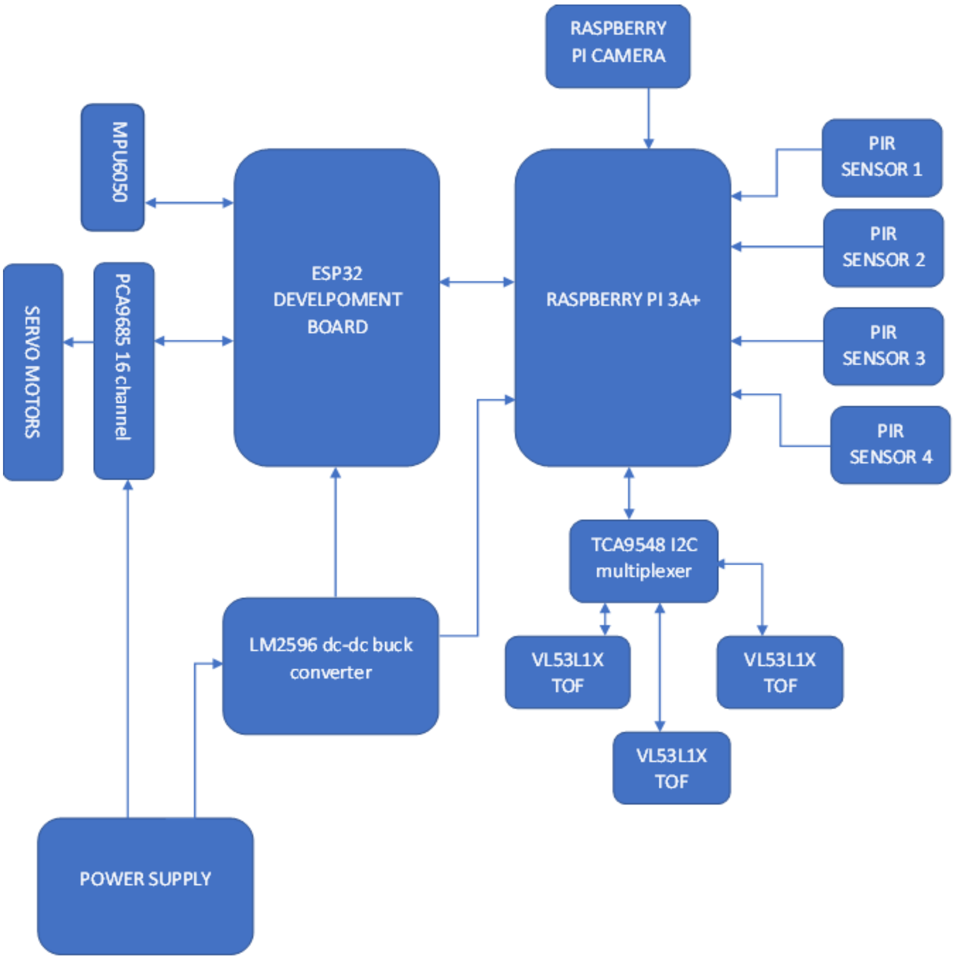

Figure 8. Block diagram

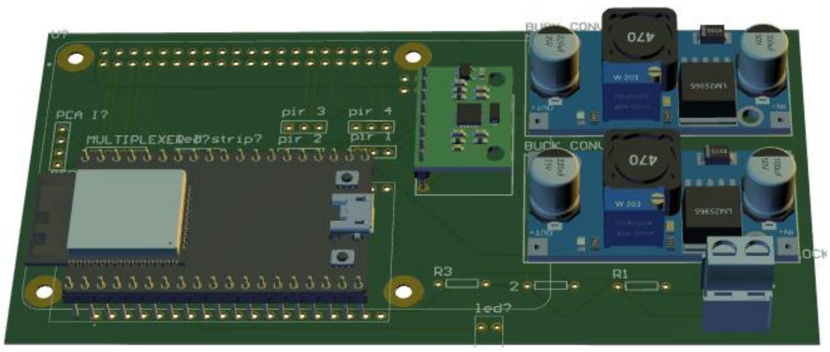

Figure 9. Circuit board design

2.2.1. Flowchart

The flow chart for developing the demonstrating the operation flow of the quadruped home surveillance robot is shown in Figure 10.

2.2.2. Body structure

The robot's body has a height of 20 cm, a brength of 18 cm and a length of 30 cm. it makes use of 3 servo motors per leg with a total of 12 servo motors for all. The CAD diagram is illustrated in Figure 11. The frame is held together by 16 mm, 12 mm, 20 mm M3 screws and 10 mm M4 screws and uses 684zz bearings to prevent friction in the joints.

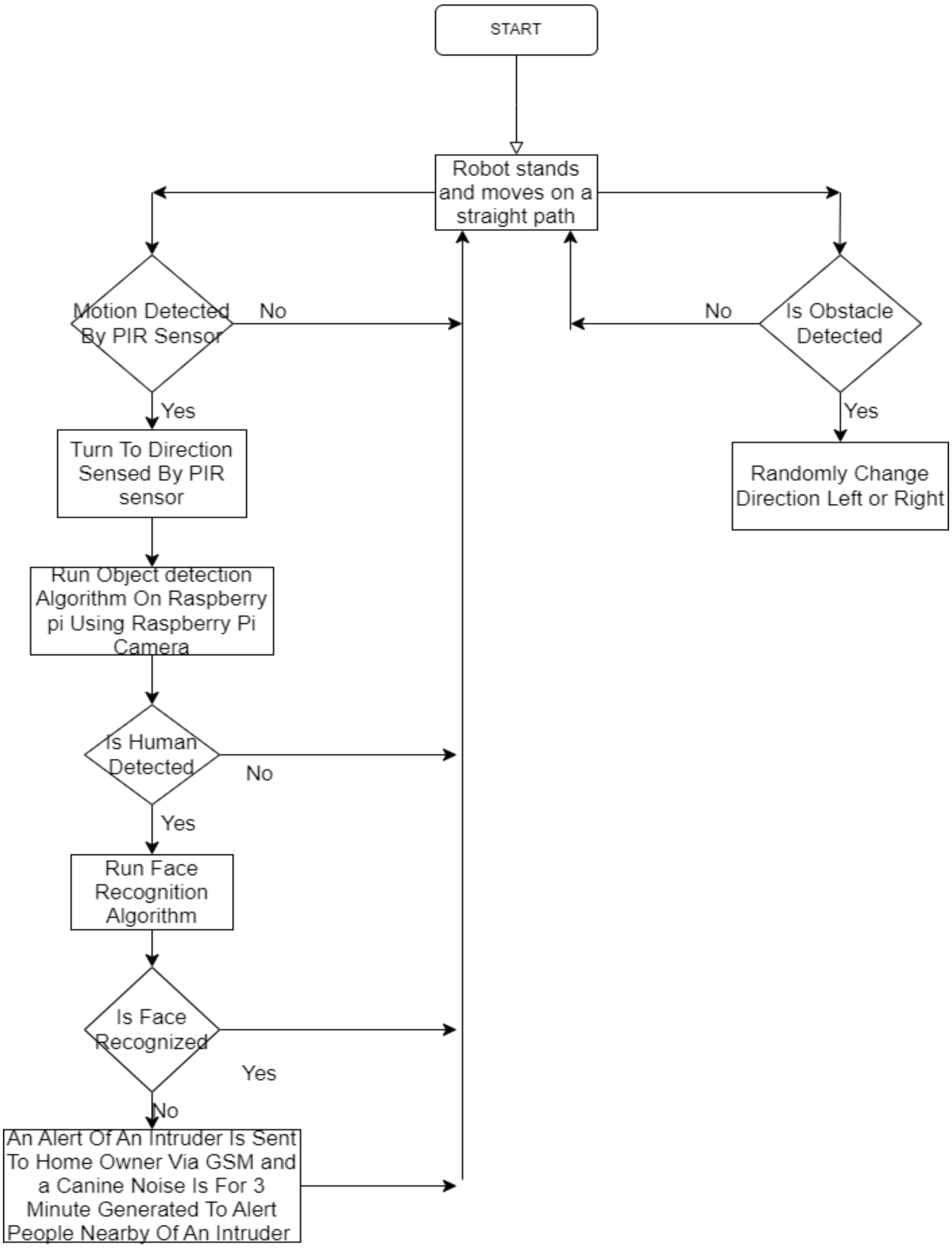

Figure 10. Flowchart

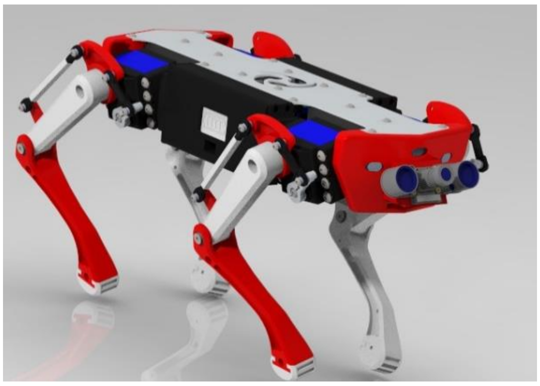

Figure 11. CAD diagram

2.2.3. Inverse kinematics calculations

Once the forward kinematics are established, inverse kinematics is needed to control the joint settings. A group of researchers derived the value of the angle for the inverse kinematics which is shown [24]. Determining θ_1 utilizing the front view of the robot leg as shown in Figure 12.

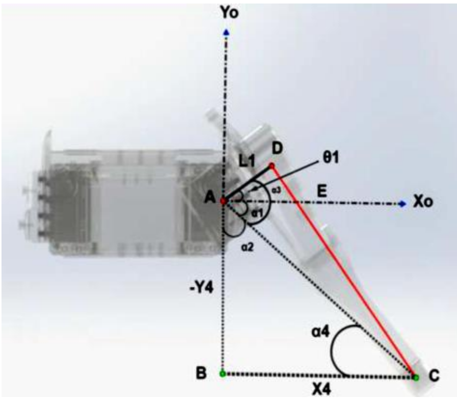

Figure 12. Robot leg

$$\theta_1 = \alpha_3 - \alpha_1 \quad (1)$$

In △ADC,

$$\propto_3 = \arctan\left(\frac{\sqrt{x_4^2+y_4^2-L_1^2}}{L_1}\right) \quad (2)$$

In _ABCE,

$$\Rightarrow \propto_1 = 90° - \propto_2 \quad (3)$$

Furthermore, in △ABC,

$$\propto_2 = 90 - \propto_4 \quad (4)$$

Substituting this value into (4):

$$\propto_1 = 90° - (90 - \propto_4) \quad (5)$$

$$\Rightarrow \propto_1 = \propto_4 \quad (6)$$

In △ABC,

$$\propto_4 = \arctan\left(\frac{-y_4}{x_4}\right) \quad (7)$$

Now, substituting the values of α_1 and α_3 into (2),

$$\Rightarrow \theta_1 = \arctan\left(\frac{\sqrt{x_4^2+y_4^2-L_1^2}}{L_1}\right) - \arctan\left(\frac{-y_4}{x_4}\right) \quad (8)$$

Determining θ_2,

$$\theta_2 = -90° + \propto_1 \quad (9)$$

From □ABFE,

$$\propto_1 = 90° - \propto_2 - \propto_3 \quad (10)$$

From △ABC,

$$\propto_3 = \arctan\left(\frac{-z_4}{\sqrt{x_4^2+y_4^2-L_1^2}}\right) \quad (11)$$

From △*ACF*,

$$\propto_2 = \arctan\left(\frac{CF}{AF}\right) \quad (12)$$

Furthermore, from △*CDF*,

$$AF = L_2 + L_3 \cos\theta_3 \quad [AD = L_2] \quad (13)$$

Similarly,

$$\propto_2 = \arctan\left(\frac{L_3 \sin\theta_3}{L_2+L_3\cos\theta_3}\right) \quad (14)$$

Now, substituting the values of $a2$ and $a3$ into (16),

$$\propto_1 = 90° - \arctan\left(\frac{L_3 \sin\theta_3}{L_2+L_3\cos\theta_3}\right) - \arctan\left(\frac{-z_4}{\sqrt{x_4^2+y_4^2-L_1^2}}\right) \quad (15)$$

From (13),

$$\theta_2 = -\arctan\left(\frac{L_3 \sin\theta_3}{L_2+L_3\cos\theta_3}\right) - \arctan\left(\frac{-z_4}{\sqrt{x_4^2+y_4^2-L_1^2}}\right) \quad (16)$$

Determining θ_3.

$$\theta_3 = 180° - \propto \quad (17)$$

In △ACD,

$$\Rightarrow\ cos \propto = \frac{AD^2+CD^2-AC^2}{2 \cdot AD \cdot CD} \quad (18)$$

In △ABC,

$$AC^2 = x_4^2 + y_4^2 + L_1^2 + Z_4 \quad (19)$$

Now, substituting the value of AC2 into (32),

$$\propto = \arccos\left(\frac{L_2^2+L_3^2-X_4^2-Y_4^2-L_1^2-z_4^2}{2L_2L_3}\right) \quad \begin{bmatrix} AD = L_2 \\ CD = L_3 \end{bmatrix} \quad (20)$$

$$\theta_3 = 180° - \arccos\left(\frac{L_2^2+L_3^2-X_4^2-Y_4^2-L_1^2-z_4^2}{2L_2L_3}\right) \quad (21)$$

Therefore, θ_1, θ_2 *and* θ_3 [25]–[27]

$$\theta_1 = \arctan\left(\frac{\sqrt{x_4^2+y_4^2-L_1^2}}{L_1}\right) - \arctan\left(\frac{-y_4}{x_4}\right)$$

$$\theta_2 = -\arctan\left(\frac{L_3 \sin\theta_3}{L_2+L_3\cos\theta_3}\right) - \arctan\left(\frac{-z_4}{\sqrt{x_4^2+y_4^2-L_1^2}}\right)$$

$$\theta_3 = 180° - \arccos\left(\frac{L_2^2+L_3^2-X_4^2-Y_4^2-L_1^2-z_4^2}{2L_2L_3}\right)$$

The Denavit-Hartenberg (D-H) table detailing the position of the leg at resting position and standing position is shown in Tables 1 and 2 respectfully. The length of the different part of the leg measured from each part of the leg is as:
L_1 = 60 mm [length of cortex]
L_2 = 115 mm [length of the femur]
L_3 = 135 mm [length of the tibia]

Table 1. D-H table for resting position

The Frame	a_{i-1}	α_{i-1}	d_i	$\theta°_i$
0 – 1	60	0	0	0
1 – 2	0	-90°	0	90°
2 – 3	115	0	0	-81.5°
3 – 4	135	0	0	-27.9°

Table 2. D-H table for standing position

The Frame	a_{i-1}	α_{i-1}	d_i	θ_i
0 – 1	60	0	0	0°
1 – 2	0	-90°	0	90°
2 – 3	115	0	0	-59.0°
3 – 4	135	0	0	2.3°

3. RESULTS AND DISCUSSION

The multiple parts, sensors and actuators were coupled to form the complete system. The system was then tested to see if the desired objectives had been achieved. The sensors and the actuators were tested separately before they were integrated into the frame/housing of the project. The integrated system was tested based on its weight, speed of robotic movement in a straight line, response to objects in the system pathway, ability to detect humans and send a message to the appropriate individuals as well as sound alarms.

3.1. Component assembly

The various stages of the assemblage of the robot are shown in Figure 13. The top and side view of the exact quadruped robot is shown in Figures 14 and 15, respectively.

Servo motors only Servo motor and developed Vero board

Figure 13. Quadruped robot 3D printed frame

Figure 14. Top view of completely assembled quadruped robot

Figure 15. Side view of completely assembled quadruped robot

3.2. Camera

The camera module used had an image sensor with a resolution of 5MP and its infrared (IR) filter was removed enabling it to capture infrared light. This enabled the camera to be able to capture more details even where visible light was low, when the camera was paired with an IR light source it provided lighting in dark conditions without revealing the light source and the potential video capture to a potential intruder. Videos captured from the camera were captured at 60 fps at 1080 p providing a good image quality that can be further worked on.

3.3. Face recognition test

The necessary Python library for OpenCV facial recognition was compiled on the Raspberry Pi. It took about 12 hours for the necessary library to be compiled into the Raspberry Pi. The faces of the members in the group were captured in order to let the face recognition software have a database to where it can compare images. Once the images had been captured and the database created, we ran the facial recognition software. The facial recognition was able to detect the faces of up to three members of the group simultaneously. Figure 16 shows the face recognition program in action.

Figure 16. Face recognition program identifying the face of the group members

3.4. Object detection test

The TensorFlow lite library was installed on the Raspberry Pi. The codes that will allow object detection from the GitHub repo were downloaded onto the Raspberry Pi. After downloading the additional files, i.e., the dataset, and enabling the Raspberry Pi camera in the Raspberry Pi configuration. the object detection model was run, it was able to detect objects such as a keyboard, phone, and most importantly, a person, at two to four frames per second (2-4 fps), which made the video stream very choppy. To remedy the choppy video the object detection program was optimized to detect only humans/persons. Figure 17 shows the object detection program detecting person, chair and laptop

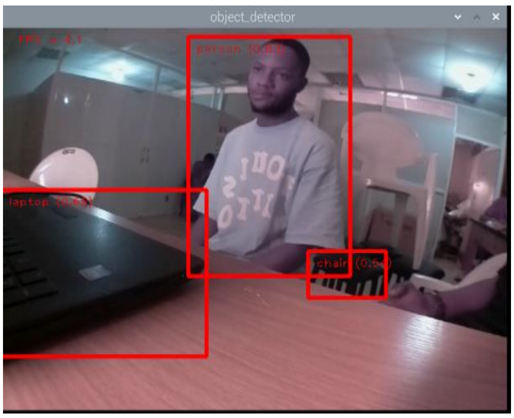

Figure 17. Object detection program detecting a person, chair and a laptop

3.5. Time of flight sensor test

The time-of-flight sensor provides the quadruped robot with the ability to detect its surroundings. The Time-of-flight sensor, despite its smaller size is capable of performing the same distance measurement as an ultrasonic sensor without the disadvantages of an ultrasonic sensor. The time-of-flight sensor was set up with the Raspberry Pi, connecting each wire to its appropriate location on the board (the VCC, GND, SCL, and SDA pins). On the software part, the VL53L1X time of flight sensor library for the Raspberry Pi and the code that would allow the Pi to read its value was downloaded from a GitHub repo. The result of the sensor test is shown in Figure 18 showing the accuracy of the sensor.

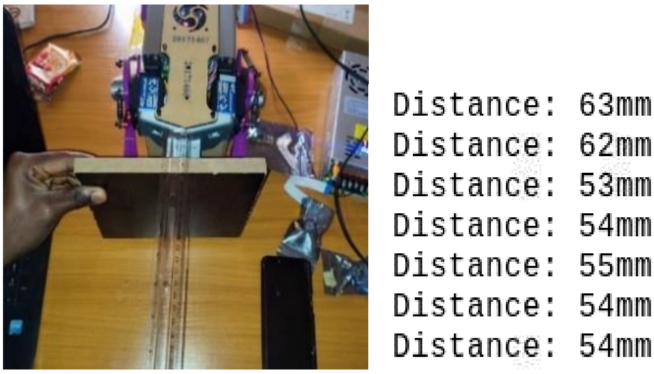

Figure 18. Time of flight test at 5-6 cm

3.6. Quadruped robot weight

From the structural analyses, the use of a 30 kgcm servo motor enables the tibia (which holds most of the weight of the robot) to hold about 3 kg of the entire weight of the robot at 10 cm from the ground. The quadruped robot weight robot was measured using a scale and a weight of 1,375 kg was obtained. This weight of the robot enabled it to be able to carry itself well as it moved across the ground.

3.7. Quadruped speed

The speed of the quadruped robot was measured by making the robot walk in a straight line with a distance known, measuring the time taken by the robot to move from point A to point B. The speed gotten was 0.08 m/s.

3.8. Endurance test/battery test

The quadruped robot was placed on an elevated platform with the leg suspended in the air to prevent the robot from moving around and test the battery life. The robot was powered on and the codes were executed. From the test, it was seen that the quadruped robot was able to operate for an average time of 30 minutes. Another test was performed on the robot while it was idle, in this case, the robot was left standing on all four legs for a while. It was noted that the battery was able to last an average of 1 hour.

3.9. Performance test

The system was powered by an 8.4 V onboard power supply consisting of three 18,650 batteries connected in parallel and connected in series with another three 18,650 batteries connected in parallel. After powering the robot using a power switch, the robot's legs move to a crouch position. The robot then stands up fully, waits for 2 seconds and starts moving forward. Once an obstacle is detected in front of the robot it changes its direction of motion to either left or right. When a human appears in front of the camera, the robot detects the human and makes a barking noise to alert nearby people to the intruder and then runs the facial recognition program. If the human is unknown to the robot, it sends a message to the homeowner alerting them of the intruder. The robot captures and saves the picture of the intruder which can be viewed later by the homeowner.

4. CONCLUSION

Home surveillance is a growing field of interest for many people who want to protect their property and privacy from intruders, thieves, or other threats. The use of a quadruped robot for home surveillance ensures that more ground is covered when monitoring the home. The quadruped robot using a high voltage servo-motor, time of flight sensor, 5MP camera and PIR sensor was successfully developed and tested.

The system has been able to identify a human being using the TensorFlow library and also identify the face of the human being, detect obstacles in its pathway using the time-of-flight sensor, send a message to the homeowner if an intruder is detected and alert nearby people using a canine communication alert system. The quadruped robot was designed and developed using low-cost and easy-to-access material making the overall build of the system cost-efficient. The result of the test showed that the system can work around a specified space for about 20 minutes.

In summary, quadruped home surveillance solved the need for an advanced and interactive home security solution that addresses the limitations of traditional surveillance systems. The quadruped robot was designed to be reliable and efficient making it a suitable solution for a variety of home security operations.

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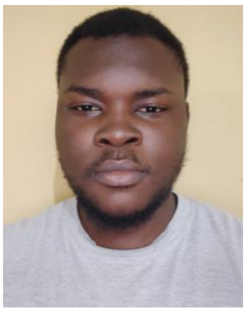

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