Autonomous Fire Detection Robot Using Modified Voting Logic

by

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Abstract:

Recent developments at Fukushima Nuclear Power Plant in Japan have created urgency in the scientist community to come up with solutions for hostile industrial environment in case of a breakdown or natural disaster.

There are many hazardous scenarios in an indoor industrial environment such as risk of fire, failure of high speed rotary machines, chemical leaks, etc. Fire is one of the leading causes for workplace injuries and fatalities[1]. The current fire protection systems available in the market mainly consist of a sprinkler systems and personnel on duty. In the case of a sprinkler system there could be several things that could go wrong, such as spraying water on a fire created by an oil leak may even spread it, the water from the sprinkler system may harm the machinery in use that is not under the fire threat and the water could potentially destroy expensive raw material, finished goods and valuable electronic and printed data.

There is a dire need of an inexpensive autonomous system that can detect and approach the source of these hazardous scenarios. This thesis focuses mainly on industrial fires but, using same or similar techniques on different sensors, may allow it to detect and approach other hostile situations in industrial workplace.

Autonomous robots can be equipped to detect potential threats of fire and find out the source while avoiding the obstacles during navigation. The proposed system uses Modified Voting Logic Fusion to approach and declare a potential fire source autonomously. The robot follows the increasing gradient of light and heat intensity to identify the threat and approach the source.

Dedication

This thesis is dedicated to my parents without whose prayers I would not have been able to finish this work, and to Faiqa, whose love, encouragement and support helped me in this journey of mine, and last but not least to Muawiz, Zahra and Zainab whose innocent questions, suggestions, words of encouragement and prayers opened so many doors for me.

Acknowledgements

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I would also like to thank (late) Dr. Atef Fahim who saw the capability in me the first time and took me under his supervision.

Also I would like to express my thanks to my colleagues in the lab whose ideas, help and support played a big part in the completion of this thesis.

Most importantly I would like to thank the Creator who made everything possible for me to achieve and gave me strength, courage and guidance to go through this phase of my life.

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Chapter 1
Introduction

1.1 Motivation:

An industrial environment is full of hazards for the workers. There are safety and security system guidelines in place but there is always room for improvement. After the Fukushima Nuclear Power Plant disaster in Japan the need of monitoring whole industrial environment has caught the attention of researchers around the world. These hazards may be chemical leak, machinery breakdown causing dangerous situations or industrial fire.

Industrial fires are a leading cause of workplace injuries and fatalities. According to NFPA (National Fire Protection Agency, USA) 2012 statistics, [1]

- 1,375,000 fires were reported in the U.S during 2012.
- 2,855 civilian fire deaths
- One civilian death occurred every 3 hours and 4 minutes
- 16,500 civilian fire injuries
- One civilian injury occurred every 32 minutes
- $12.4billion in property damage
- A fire department responded to a fire every 23 seconds
- 480,500 of these fires were structure fires.

Fire is an abrupt exothermic oxidation of materials that generates light, heat, gases and some other by-products**.** If in control, fire is very helpful to humans but if not contained, in some cases it can be disastrous. [2] The best way to not arrive to a threatening situation is to detect unwanted fire in its early stages and extinguish it before it spreads to other combustible objects nearby.

This work is particularly important in the case of having a monitoring done at night or days where active surveillance cannot be performed by a human.

There is a need of an autonomous robot that can detect potential threats of fire in a workshop and approach the source autonomously while avoiding the obstacles during navigation.

There are security systems in place in factories that keep the workers safe, for example, in case of fire, a sprinkler system will be activated helping to contain fires. However, a sprinkler system may make a larger area wet which could not only be harmful for the machines but also sometimes that could cause a loss of millions of dollars by destroying raw materials or finished goods that should not be exposed to water. In case of a sensitive office building, it may destroy valuable data stored in the computers. Also some industrial fires actually grow more or are not affected by the use of water as oil being lighter than water will still burn after thrown water on.

The most efficient way to put out a fire will be using a fire extinguisher at the source of fire not the whole workshop, after the fire source is declared using an autonomous fire detection robot. This will also ensure that the production or the work is not stopped in the whole organization and the areas not under threat of fire are undisturbed.

1.2 Research Objective:

In order to increase the productivity of the currently available options, a robot will need to scan an area of interest, detect and approach the source of fire accurately and consistently while avoiding the obstacles autonomously. This robot should have very few false negatives and false positives, i.e., declaration of a fire when no fire is present and non declaration of fire where a fire is present. Also this robot should be able to distinguish between a less likely and a more likely source of fire and prioritize its investigation.

Certain scenarios will need to be tested and the approach will be refined by using the mathematical expressions and experimental results.

There are three main scenarios that will be tested.

1. Fire in plain sight of the robot,
2. Fire incident behind an opaque wall and a reflective wall in front reflecting only the light,
3. Fire incident behind an opaque wall and a non reflective wall present close to the opening.

1.3 Method of Approach

To perform the tasks outlined in the scenarios described above, the method chosen is “Voting Logic Fusion”, since it was determined that voting logic has the ability to detect suppressed or noisy targets and also has significant target identification properties. Voting logic is important in many ways It is used to fuse explicit or implicit data originating from multiple sources for realizing an ultra-reliable system based on multichannel computational paradigm. [3]

In order to enhance the capability of this approach a new modified voting logic approach is presented that combines the sensitivity of the system and also keeps into account the principal variable in fire (heat) into account. It not only presents the singleton sensor mode for the declaration of fire but also presents a three sensor based non-possibility scenario to deter against false alarms. One temperature and two light sensors are used to perform the initial tasks. For a second set of experiments, two thermal infrared sensors and one light sensor is used. Also one sonar (ultrasonic) sensor is mounted on the robot for obstacle avoidance independent of the other sensors. This sensor does not take part in declaration of fire but is of utmost importance for the robot to safely arrive at the fire source.

Since there are light and heat sources present and the light and heat is reflecting off the walls and there are multiple reflections of these variables, to get consistent relevant results the focus of the thesis is on direct experimental results and not on simulation, as each scenario is environment specific and cannot represent another possible case of fire detection.

1.4 Thesis Outline:

This thesis consists of 9 chapters that walk the reader through different stages of work.

Chapter 2 provides a literature review of previously published research from scientists working on similar technology around the world. It also discusses the advantages and limitations of such work.

Chapter 3 presents the robot used, the reason for this choice, the advantages, qualities, limitations and challenges of using it. It also describes the kinematics of the robot.

Chapter 4 discusses the properties of light and heat and how the strength of signals varies at different distances and includes relevant graphical representations.

Chapter 5 describes the navigation strategy of the robot and presents the advantages of using the sinusoidal motion approach. It also includes the “VI” or Virtual Instrument, (another name of LabVIEW programs) designed to achieve this motion pattern.

Chapter 6 introduces the “Voting Logic” approach and explains the different parts of it such as confidence levels, sensor fusion, block diagrams and prepares the reader to understand the approach considering the robot available.

Chapter 7 explains the "Modified Voting Logic", its implementation, confidence level calculations, detection modes, fire declaration algorithm, its derivation and explanation. It also presents the calculations of probabilities of detection and false alarms.

Chapter 8 details the experimental results and also discusses certain scenarios. It also includes the commentary for using different sensor arrangements and modifications of the hardware where necessary

Finally, Chapter 9 concludes the thesis by discussing the results, conclusions drawn and providing recommendations for further research.

Chapter 2
Literature Review

In their paper, Oleh Adamiv et al. [4] have suggested a regular iterative method of gradient search based on the local estimation of second order limits. They suggest this improved method of robot local navigation based on the use of potential fields for movement taking into account the gradient of direction to the goal. They discuss the environment for Autonomous Mobile Robot (AMR). In their research, they take into account that the robot follows the artificial potential fields and has enough clearance from the obstacles to perform manoeuvres safely. The direction of movement is chosen from alternative solutions where the value of cost function is largest. In order to determine the optimal movement path with any influence of AMR of two or more obstacles, the sum of the cost function values is used based on least-squares method. The navigation of AMR consists of two stages in this paper, namely the movement to the goal using gradient of direction to the goal and the value of cost function of obstacles, and obstacle avoidance along perimeter.

Hu Huosheng, et al. [5] in their paper "Sensors and Data Fusion Algorithms in

Mobile Robotics" have provided a broad overview and understanding of sensor technologies and data fusion algorithms that have been developed in robotics in general and mobile robots in particular, with a scope for envisaging their important role in UK robotics research and development over the next 10 years. The key theme of this report is to present a brief review on sensor technology. It includes a brief description of the current advancement of a range of sensors and data fusion algorithms and the reason why it is so hard. Then, a brief summary on sensor and data fusion algorithm development in the UK is presented, including its position in the world.

E. Zervas et al in the paper “Multisensor data fusion for fire detection” [6], 2008, discuss the forest fire detection by using the fire detection method constituting of fusion of temperature, humidity and vision sensors. Each sensor reading is transmitted to a centralized control unit. A belief of fire probability is established for each resultant node, and then this data is fused with the vision sensors that monitor the same geographical area. In the first level the data is fused but in the second stage, the information is also fused to establish a confidence level of possibility of fire. The first level data fusion consists of gathering the required data from in-field and out-field sensors. It then goes through the process of recognition of smoke or flame or in case of in-field sensors it looks for changes in distribution of data. If there is a detection and distribution change is detected then the second level (Information Fusion) comes into effect where collection of probabilities, fusion of probabilities and reasoning about the fire is established.

In the paper "Autonomous Fire Fighting Mobile platform", Teh Nam Khoon[7], et al. have come up with a novel design of an autonomous robot. This robot, as called by them, Autonomous Fire Fighting Mobile Platform or AFFPM, has flame sensor and obstacle avoidance systems. The AFFPM follows a preset path through the building and uses a guide rail or markers such as black painted line or a tape to navigate through the environment until it detects an elevated chance of a fire being present. At that point it will leave its track and follow the fire reaching within 30 cm of the flame. It then would engage the fire extinguisher that is mounted on the platform. Once it has left the navigation route, the obstacle avoidance will start to perform and it will be able to guide the AFFPM precisely closer to the source of the fire. When it has extinguished the fire completely it would then return to its guiding track to carry on with its further investigation of any other fire sources.

Flame detection in the AFFPM has its limitations as it can only scan the area in front of the flame detection sensor. Typically the angle of vision of such sensor is 45º. If, however the robot is programmed to make a 360º turn every now and then, it would increase the area of vision of the robot, slowing down the robot significantly. Also it would be using more area for navigation as the track has to have paths circling in a 360˚ in every new room it enters on its way. Typically this robot would go into each room of the establishment, after a set period of time and perform the required actions, such as scanning for and extinguishing the fire.

In the paper, "Distributed Detection With Multiple Sensors: Part I—Fundamentals"[8], Ramnayayan Wiswanath and Pramod K. Varshney discuss some basic results on distributed detection. They have discussed series and parallel architectures and the governing decision rules that may be implemented. They also talked about optimization based on Neyman-Pearson criterion and Bayes formulation for conditionally independent sensor observations. The optimality of the likelihood ratio test (LRT) at the sensors is established. General comments on several important issues are made including the computational complexity of obtaining the optimal solutions, the design of detection networks with more general topologies, and applications to different areas.

In the paper “Cooperative Detection of Moving Targets in Wireless Sensor Network Based on Fuzzy Dynamic Weighted Majority Voting Decision Fusion” Ahmad Aljaafreh, and Liang Dong[9] discus the advantages of weighted majority voting decision making to detect targets.

In another Voting Logic approach, A Boolean Algebra Approach to Multiple Sensor Voting Fusion, Lawrence A. Klein [10] introduced an algorithm to solve the maze that avoids the long process to save time and memory. The proposed algorithm is based on image of the maze and the algorithm works efficiently because of the pre-processing on the entire maze`s image data before the robot starts navigation, so the robot will have information about the maze and all the paths; only capturing the image and processing it will be enough to make the robot navigate to the target without searching because the path will be known and this will give the robot preplanning time and selection of the method before falling in mistakes like loops and being trapped in a local minimum. In this research an algorithm to solve maze discovery problem has been produced, based on an image of the maze, to create and pre-processing the data of the entire maze. This avoids the robot traversing long pathways and saves time and memory. Even if it fails to cover the entire maze it still better then navigating the whole maze cell by cell. Results show that not all walls are detected properly and this means that image processing techniques go to approximate half of the maze. For complete solution it doesn't give proper results, so it is better if it is done in process as long as the robot approaches to the end and tries to capture more images so it gets more accurate results. Image processing does not give the complete solution; if the image would have been taken from the top of the maze this would work better, but in this situation it's not completely appropriate.

D. Necsulescu and Adeel ur Rehman [11] have discussed the "Modified Voting Logic", different sensor arrangements and some experimental results claiming that modified voting logic for target declaration is a valuable technique to identify industrial fires in an indoor environment. This thesis is based on that paper.

The above works have great contribution to the field but there is a possibility of using another more productive way of detection and declaration of industrial fires using a modified voting logic fusion, the approach chosen for investigation in this thesis.

Chapter 3
The Robot NXT 2.0

The robot used for these experiments is a non holonomic differentially driven robot called Mindstorms NXT ®. This light weight easy to assemble robot was chosen due to the following qualities:

- Lightweight
- Inexpensive
- Easy to build
- Can be programmed in LabVIEW
- Quite accurate and precise
- Is capable of quick changes in the hardware as required by the user
- Is compatible with a number of sensors including light, color, proximity, touch, PIR, TIR, gyroscope and other sensors.

Some of the limitations include

- Only four inputs can be connected at one time
- Very low profile on the ground
- Slow
- Does not have support for smoke sensors

The robot can be constructed in accordance to the user's needs. It consists of four input ports and three output ports. The input ports are capable of receiving signals from a variety of sensors including ultrasonic, TIR (Thermal infrared), light, color and touch sensors.

The output ports can run three different motors which can either mobilise the robot or perform certain actions. The input ports are denoted as numbers 1 through 4 and the output ports are named as the first three alphabets namely A, B and C. Using the same nomenclature the sensors would be referred as Sensor 1, 2, 3 and 4 respectively and the corresponding motors to the ports would be denoted as Motor A, Motor B and Motor C respectively. The processing unit of this particular robot is called the “brick”. The brick is generally placed in the middle of the robot being the biggest unit. This could also be considered as the central processing unit of the robot.

Here is a quick description of different parts of the robot.

3.1 Programmable 32-bit Brick

Figure 3. 1 Programmable NXT Brick

The NXT Brick™ is the center of the system. It features a powerful 32-bit ARM7 microprocessor and a flash memory. It also includes support for Bluetooth ™ and USB 2.0. It has 4 input ports and 3 output ports. It is powered by six AA (1.5 V) batteries. A better choice for the batteries is Lithium Rechargeable Batteries. At one time up to three bricks can be connected however only one brick can be communicated at one time. It has a programmable dot matrix display. It also allows you to use a number of pre-defined commands directly on the brick.

3.2 Inputs for Mindstorms ™

3.2.1 TIR (Thermal Infrared Sensor)

Figure 3. 2 Dexter Industries Thermal Infrared Sensor

The Thermal Infrared Sensor or TIR used in the experiments in this thesis was manufactured by Dexter Industries. This choice was made because of the qualities that this sensor possesses. It is completely compatible to be used with the Brick. A brief description of this sensor follows:

- Capable of reading surface temperature of the objects from a distance
- It can read object temperatures between -70°C and +380°C.
- It has an accuracy of 0.5°C and a resolution of 0.02°C.
- Capable of reading both ambient and surface temperatures
- It is also capable of reading the emissivity values.
- The software patch to allow it to be used with LabVIEW ® was downloaded from the download section of Dexter Industries support website.
- This sensor has an angle of vision of a total of 90°, 45° of which are to the positive and the other 45° is on the negative side of the normal axis.

3.2.2 SONAR (Ultrasonic Sensor)

Figure 3. 3 Ultrasonic Sensor for Mindstorms® NXT

- Consists of two sensors 3 cm apart horizontally
- The Ultrasonic sensor is able to detect an object in the way
- It is also capable of measuring its proximity in inches or centimeters

- Maximum range is 255 cm. When the objects are further away from this distance, it returns the maximum value that is 255 cm.
- Compatible with Mindstorms ™ NXT 2.0
- It measures approximate distances and needs to be calibrated against physical values for greater precision. Its accuracy is +/- 3cm.
- The distance of the object detected by the ultrasonic sensor depends upon the ultrasonic reflectance of the object's composition and size.
- It detects larger hard objects from a greater distance compared to the small soft ones.
- The sensor detects objects right in front of it at greater distances than objects off to the sides. [12]
- The Ultrasonic Sensor uses the same scientific principle as bats: it measures distance by calculating the time it takes for a sound wave to hit an object and come back – just like an echo.

3.2.3 Color and Light Sensor

Figure 3. 4 Color Sensor for Mindstorms ® NXT

- Using the NXT brick, the Color Sensor is able to perform three unique functions.

- It acts as a Color Sensor distinguishing between six colors
- It works as a Light Sensor detecting light intensities for both reflected and ambient light.
- It works as a Color Lamp, emitting red, green or blue light.
- It detects colors using separate Red, Green and Blue (RGB) components
- The angle of vision of this sensor is also 45° on either side of the normal axis.
- To detect color, it needs to be very close to the colored object (1~2 cm).
- Its output values also range from 0 to 255 for the luminance. [13]

3.3 Outputs for Mindstorms ™

Mindstorms robot used in the experiments has three output ports, described as A B and C respectively. These output ports are connected to Servo Motors with built in rotation sensors.

3.3.1 Servo Motor with in-built rotation sensor

Figure 3. 5 Servo Motor with Built-in Rotation Sensor

- Sensor measures speed and distance and reports back to the NXT.
- Allows for motor control within one degree of accuracy.
- Several motors can be aligned to drive at the same speed.
- Each motor has a built-in rotation sensor that lets the user control the robot's movements precisely.
- Rotation sensor measures the motor rotations in degrees or full rotations with an accuracy of +/- one degree.
- The motors automatically get synchronized by using the "move" command. [13]
- The motor speed can be programmed from 0 to 200% power indicating the speed of the motors.
- The speed of the robot due to the rotation of these motors at 100% power is 30cm/s. (0.3 m/s)

3.3.2 Other Outputs:

There are certain other outputs such as sound or a signal to the PC that may also be obtained from the NXT Brick.

3.4 The Assembly:

The robot can be assembled from these components and can either be programmed by communicating through a Bluetooth® or a USB cable connected to the computer.

It comes with *LabVIEW®* based software called *NXT-G2.0* but that can only perform basic actions. In order to perform the advanced calculations as required in this thesis, *LabVIEW®* was preferred. *LabVIEW®* has a built-in support for Mindstorms. In order to accommodate the third part sensor (the TIR sensor), a software patch from the website of Dexter Industries was downloaded. This patch enables the software to acquire the ambient, object and emissivity from the TIR sensor.

After the assembly the robot appears as follows

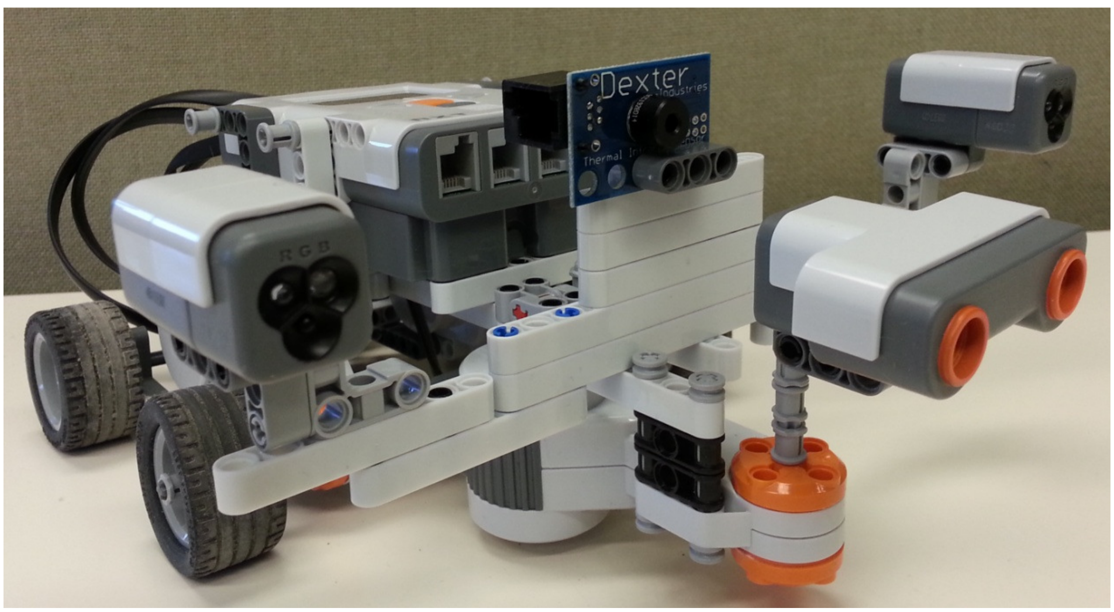


Figure 3. 6 The assembled NXT 2.0 with one TIR, two light and color sensors and one ultrasonic sensor

The ports visible to the viewer are the input ports and the ports on the other side are output ports connected to the three Servo Motors, one of them in this design is not actively used in the robot movement.

Certain ports are designated to certain sensors to avoid any programming confusion.

- Port **1** was allotted to the TIR Sensor
- Port **2** was allotted to the "Color and Light Sensor" with Green LED
- Port **3** was allotted to the "Color and Light Sensor" with Blue LED
- Port **4** was allotted to the Ultrasonic *SONAR* sensor.

Also for the output ports:

- Port **A** moves the Servo Motor A, which was used as an indication of declaration of fire.
- Port **B** powers the motor on the right side of the robot, looking from front
- Port **C** powers the motor on the left side of the robot, looking from front

The ultrasonic sensor was also mounted in the front and its job was to avoid any physical obstacles. As the robot reaches the vicinity of another object within 25 cm it would back up turning afterwards depending upon which side has a greater gradient of light and keeps detecting the elevated levels of light and heat.

3.5 Robot Operation:

As mentioned above, this is a differentially driven robot that moves depending upon the relative speeds of the driving wheels, controlled by the driving motors. Here is a brief description of the movements of the robot.

- If Motor B and C run at the same speed, the robot will move forward or backwards
- If Motor B is running forward and Motor C is stopped the robot would turn LEFT (or rotate in anticlockwise direction) with the axis origin as the center of the left wheel.
- If Motor C is running forward and Motor B is stopped the robot would turn RIGHT (or clockwise direction) about the axis origin of the center of the right wheel.
- If Motor C is running forward and Motor B is running backwards, the robot will rotate clockwise at that particular spot with the axis of movement to be the center of the robot.
- If Motor B is running forward and motor C is running backwards, the robot will rotate anticlockwise at that particular spot. With the axis of movement to be the center of the robot.
- The speed and power of these two motors can be altered to have different combinations of turns having different radii and speeds.

This is a qualitative description of the kinematics of the robot. Next section presents the mathematical model of the kinematics of the robot

3.6 Robot Kinematics

Fig. 3.7 describes the differentially driven robot

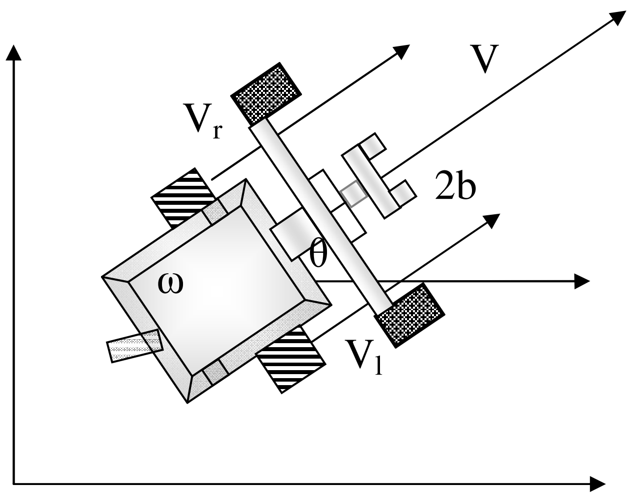


Figure 3. 7 The Model of a Differentially Driven Two Wheeled Autonomous Robot in a two-dimensional workspace.

3.6.1 Kinematic Equations of a two-wheeled vehicle

Assumptions:

- No slippage between the wheels and axel
- No Slippage allowed between the tire and terrain, meaning the relative velocity at contact point between the wheel and horizontal plane is zero.
- Steady state movement (Lightweight robot)
- 2D environment

Nomenclature:

V_l = Velocity of the left wheel,

V_r = Velocity of the right wheel,

V = velocity of the assembly,

ω = Angular velocity of the geometric center of the vehicle,

2b = Distance between wheels,

R = Wheel radius,

$\varphi_r(t)$ = Rotation angle of the right wheel

$\varphi_l(t)$ = Rotation angle of the left wheel

Non-holonomic differential robot kinematic model is given by:

$$Vx = \frac{V_r + V_l}{2} Cos\ \theta$$

$$Vy = \frac{V_r + V_l}{2} Sin\ \theta$$

$$\omega = \frac{V_r - V_l}{2d}$$

The configuration of the robot can be described by:

$$q = [x, y, \theta, \varphi_r, \varphi_l]^T \qquad (1)$$

- where x and y are the two coordinates of the geometric center of the Autonomous wheeled vehicle.
- θ is the orientation angle of the robot (Robot orientation).

The Kinematic Model of the Robot in matrix form is[14]:

$$\begin{bmatrix} v \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} R/2 & R/2 \\ R/2b & -R/2b \end{bmatrix} \begin{bmatrix} \omega_r \\ \omega_l \end{bmatrix} \qquad (2)$$

Chapter 4
Gradient Increase Approach

Relationship between distance from the light source and light intensity

Figure 4.1 shows the light intensity decrease with distance.

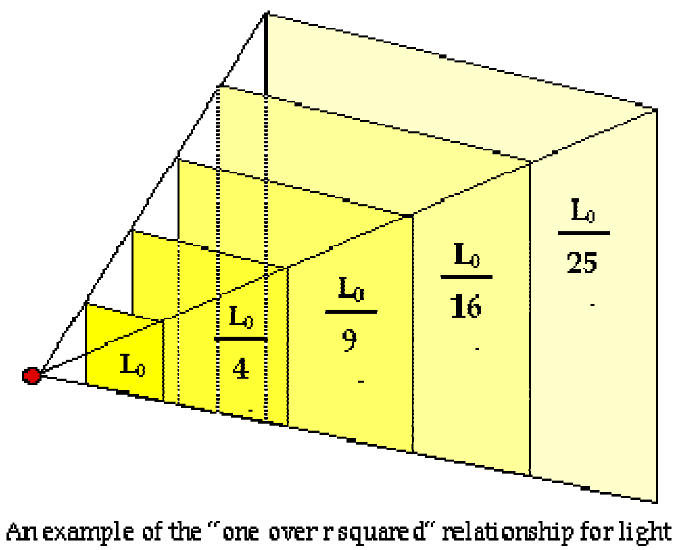


Figure 4. 1 Light intensity decrease with distance. (NASA Imagine website http://imagine.gsfc.nasa.gov/YBA/M31-velocity/1overR2-more.html)

Conversely, the increase of intensity of light traveling towards the source follows the same squared distance relationship

$$L_f = \frac{L_o}{r^2} \qquad (4.1)$$

When the sensors detect a light source, the value of incandescence will increase at this squared distance relationship in terms of distance (r) moving towards the light source.

Heat can be transferred from an object in three different ways, namely, conduction, convection and radiation. In the case of a fire source, the heat is transferred to the sensor by radiation.

The radiated heat follows the same relationship with respect to distance from the source. Hence the detected increase in temperature will not be very substantial but, as the distance to the source decreases, the increase in temperature will be exponential.

To calculate that, we have to take “solid angle” in account this has the units “Stradians” in the SI system. The conical vision of the sensors will have a detection area depending upon the angle of vision of the sensor.

One whole sphere has about 4π Stradians. We will not go into the solid angles in detail as we have made an assumption that the robot is detecting the fire source in a two-dimensional environment.

Hence the distance to the source and the intensity of light are the two factors that remain of interest.

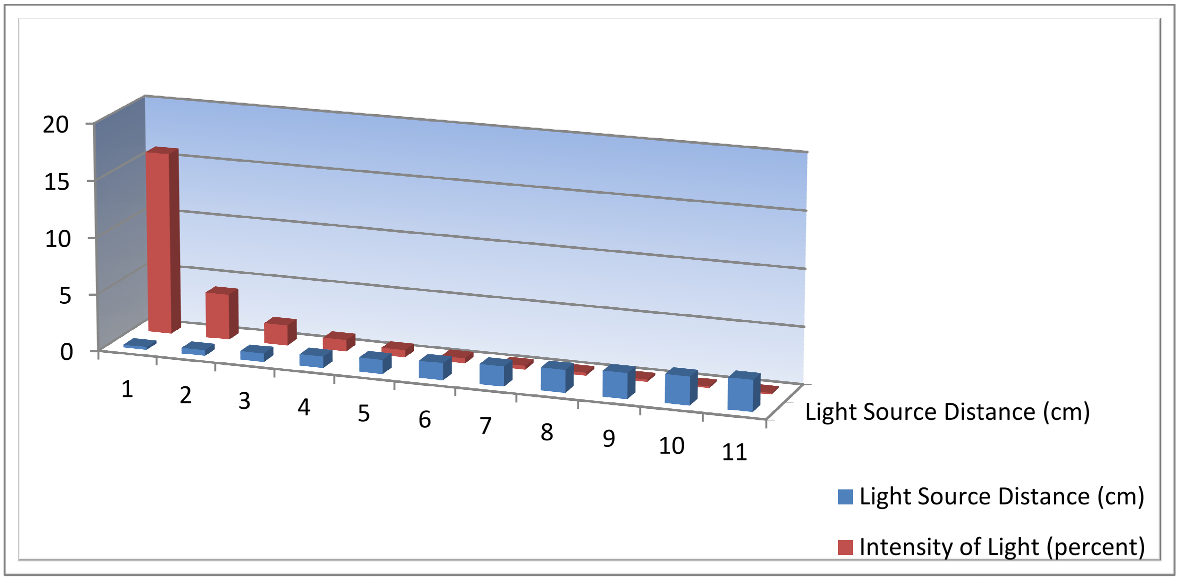


Table 4. 1 Relationship of light intensity with distance from the source

The light coming from a luminous source can be considered as a three dimensional ball increasing in size and decreasing in intensity as it travels away from the source. Figure 4.2 describes the relationship in a graphical manner.

It is possible for a sensor to detect the robot movement relative to the source by comparing the gradient of light at different positions from a source and to permit to calculate the distance and also direction of the source.

Chapter 5
Navigation Strategy

There are certain animals in the wild having sensors of different kinds. For example some snakes have IR sensors; Bats use the reflected sound waves to map their surroundings, path and prey. Also some insects such as beetles have shown some greatly evolved infrared sensing of forest fires, not to escape it but to lay their eggs in freshly burnt wood. [15]

Most of the animals including humans have two eyes, ears, hands, nostrils. That not only gives them a "stereo sensing" of the objects in question but also a perception of "depth". It is very easy for humans and most other animals to just move their neck and sense the objects around them but it becomes a more challenging when an autonomous robot has to do the same thing.

Lilienthal et al**.** in his paper "Gas Source Tracing With a Mobile Robot Using an Adapted Moth Strategy, 2003"[15] discusses different strategies adopted by different moths to detect sources of different kinds. One silkworm insect called Bombyx Mori uses a similar strategy. In that strategy, a fixed motion pattern realizes a local search and restarts the motion pattern if increased source concentration is sensed.

It results in "Asymmetric motion pattern biased towards the side where higher sensor readings are obtained hence keeping the robot in a close proximity of the source after guiding it".

The behavior of the silkworm moth Bombyx mori is well-investigated and suitable for adaptation on a wheeled robot, because this moth usually does not fly. The behavior is mainly based on three mechanisms [15]

- a trigger: if the moth's antennae are stimulated by intermittent patches of pheromones, a fixed motion pattern is (re-)started

- local search: the motion pattern realizes an oriented local search for the next pheromone patch

- estimation of source direction: the main orientation of the motion pattern that implements the local search is given by the instantaneous upwind direction, which provides an estimate of the direction to the source

Stimulation to either antenna triggers the specific motion pattern of the Bombyx males. This fixed motion sequence starts with a forward surge directed against the local air flow direction. Afterwards, the moth performs a "zigzag" walk, while it starts to turn to that direction where the stimulation was sensed. The turn angles and the length of the path between subsequent zigzag motions turns increase with each turn. Finally, a turning behavior is performed, while the turns can be more than 360 $\circ$. This "programmed" motion sequence is exactly restarted from the beginning if a new patch of pheromones is sensed. As it could be shown in wind tunnel experiments by Kanzaki [16], this behavior results in a more and more straightforward path directed towards the pheromone source if the frequency of pheromone stimulation is increased. [17]

The solution suggested is a “sinusoidal” movement to increase the visual area of the robot for the first detection of the increased intensity of a variable of interest.

Each sensor has different constraints such as distance of vision, peripheral vision, and range and accuracy limitations. The light sensors used in Mindstorms robot have a peripheral vision of 45°. That means that when this robot detects light 45° on either side of the normal axis is being searched for increased light values.

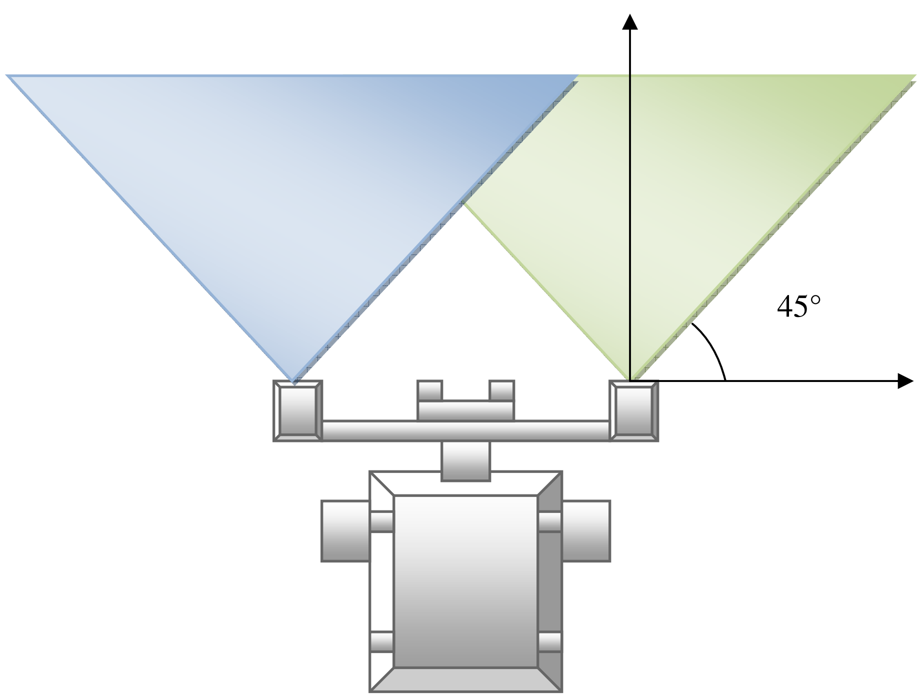


Figure 5. 1 Sensor Peripheral Vision

5.1 Sinusoidal or Zigzag Movement of the Robot

Introduction of the sinusoidal movement of the robot is important to scan a larger area for possible heat and light sources.

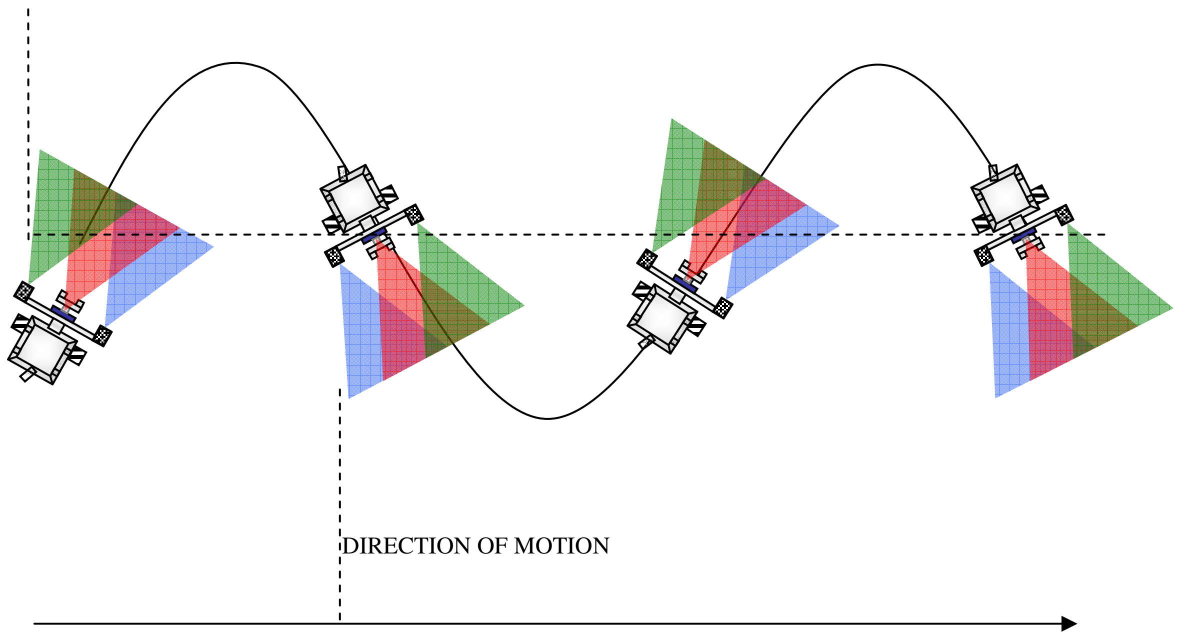


Figure 5. 2 Sinusoidal movement of the robot and scannable angles

Since the sensors are fixed on the robot and the movement of robot determines the direction of these sensors, the vision of these sensors is limited to 45˚. The sinusoidal movement used for the navigation strategy, moves the robot 45˚ to the right and 45˚ to the left while sampling the elevated levels of light or heat. This sinusoidal movement, shown in Figure 5.2, requires peripheral vision of sensors of 180˚ in the direction of motion of the robot.

In order to cover 180˚ in the direction of motion it was chosen to use a scanning approach such that, as the robot travels in a straight line, the sensors cover the area surrounding it.

The speed of the robot is 0.3 m/s at 100% power. The power can be altered from 0% to 200% to change speeds. The optimized sampling for sensors is 10 times a second. A sine wave of amplitude 1 was chosen to optimize the distance traveled, area scanned and time elapsed to complete one cycle.

Depending on the requirements, the amplitude and frequency can be chosen by the programmer. If there is a need to scan a wider area, the amplitude can be changed to a larger value number.

The robot trajectory can be simplified as a zigzag motion where it crosses the x-axis at 45° angle.

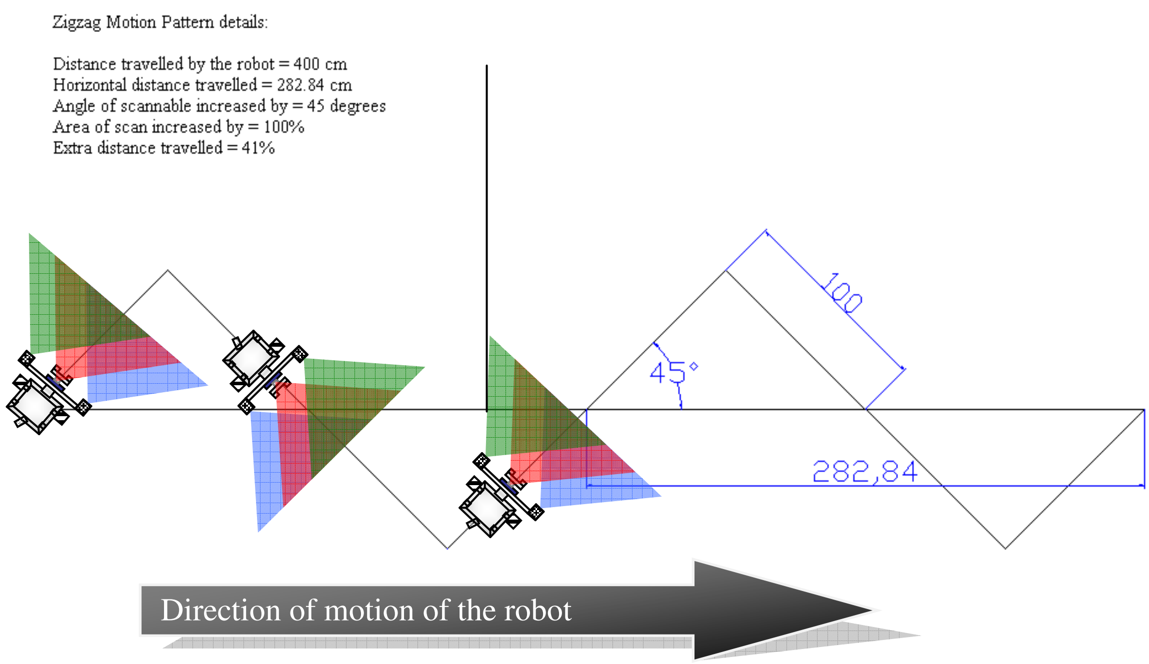


Figure 5. 3 Scannable area and zigzag motion pattern

Figure 5.4 is a representation of the scannnable area increase and extra distance travelled by the robot to scan that extra area. The robot motion, as described earlier, can be better modelled by a zigzag motion instead of a sinusoidal movement.

As described previously, the peripheral vision angle of the sensors is 45°. By the introduction of the zigzag motion pattern the peripheral vision on each side of the sensor increases to 90°, doubling its capability of detecting targets around the direction of its motion. The extra distance travelled by the robot is about 41% which can be well justified considering the increase in the scannable area on either side of the direction of robot motion.

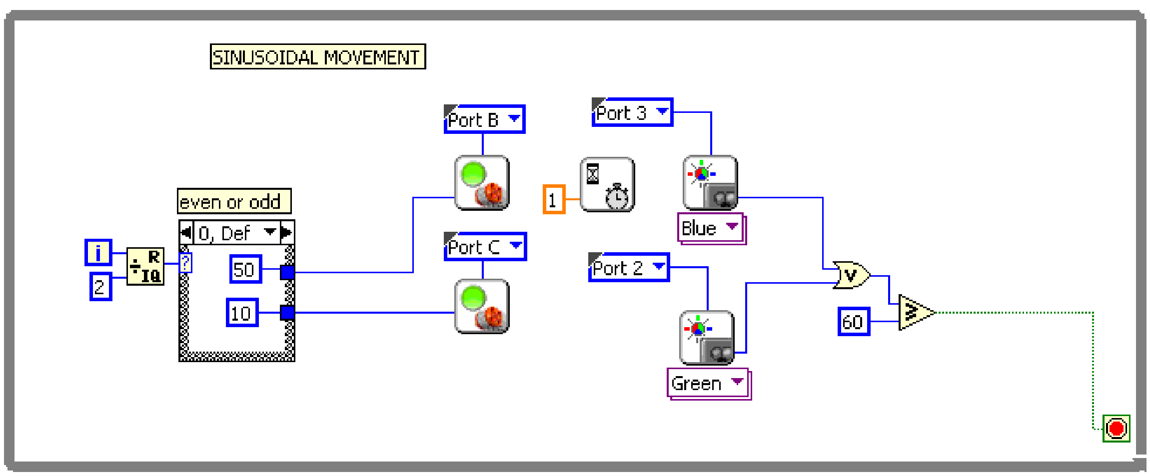


Figure 5. 4 LabVIEW Virtual Instrument (VI) for sinusoidal movement of the robot ending as higher levels of light are reached

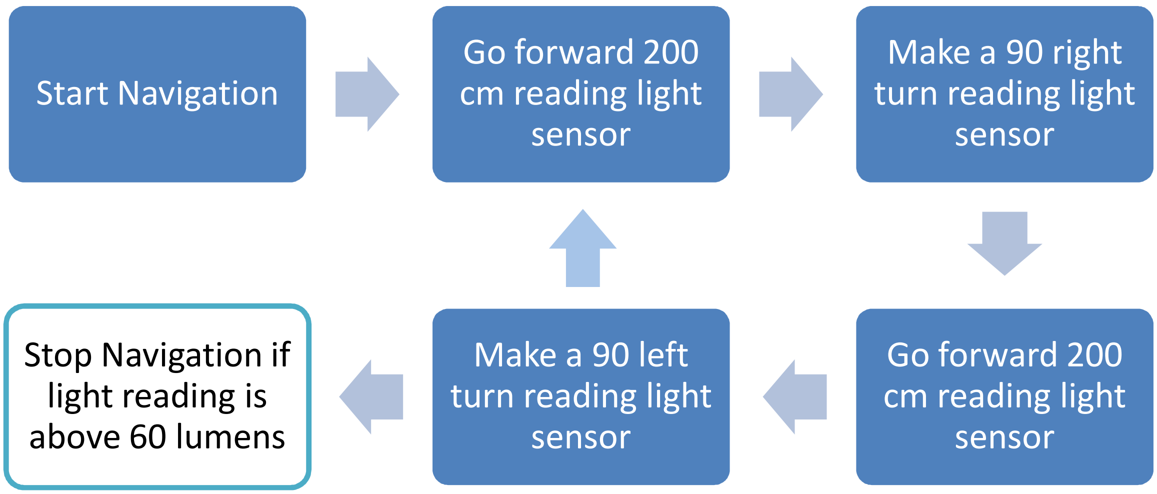


Figure 5. 5 Flow chart for the zigzag movement of robot

As previously described, the program written in LabVIEW is called a Virtual Instrument or a VI. In the above VI designed for sinusoidal movement several issues were considered. The motors of the robot are running at a predefined speed, changing their direction as the speeds of the motors are changed. For the first second, Motor B runs at 50% power while Motor C runs at 10% power essentially turning the robot right. After that one second, the same ratio is applied to the motors but it is reversed, moving the robot in the other direction, achieving a sinusoidal curve of amplitude of 1.

Two light sensors can also be observed detecting light. The sensor connected to Port 2 emits green light and the sensor connected to Port 3 emits blue light for recognition purposes. If one of these sensors detects light value more than or equal to 60 Lumens, this sinusoidal movement program terminates bringing the robot to halt. But the next level of program comes into effect which guides the robot towards the now-detected light or heat source. That strategy is discussed in Chapter 7.

Next, a description is given for tracking of the light source with one, two and three sensors. The information given in this chapter only refers to the tracking and approach of the robot to the source. Fire declaration algorithms are described later in Chapter 6 and 7.

5.2 Tracking of a heat source with one sensor

In the case of a single sensor tracking, the way to follow the increasing gradient of heat was to compare the current temperature reading with previous reading. As mentioned in Chapter 4, the gradient of light and heat would increase if the robot is approaching the source. Hence a program was designed to make the robot go straight as long as the current temperature was greater than the previous one. As soon as the comparison shifted the other way around or gave the same temperature reading as the previous reading, the robot would slightly turn right (or left). If the comparison continues to give lower or equal values, the robot will keep on going in a circle until it detects elevated temperature values and starts travelling towards it.

The TIR sensor was mounted in the front of the robot. TIR sensor gives the object temperature function of distance. As described in Chapter 4, the relationship between the light or temperature intensity increase to the distance is exponential.

For this purpose a "While loop with Shift Register" was used. The strategy developed was that the motors A and B would make the robot make a 360° turn. On the detection of elevated temperature, both motors start moving and drive the robot towards frontward.

Temperature readings are taken every 100^{th} of a second. These readings are compared to the previous temperature readings which makes the robot decide if it needs to go straight or turn.

To maximize the certainty and minimize jerky motion of the robot, an average of the last 4 readings is taken in account to be compared to the current value, producing a much smoother curve and hence smooth movement.

By comparing the previous readings and always going towards the higher reading than the previous one, the robot is able to get to the source. A predefined temperature value determines that the robot has approached close enough to the source and at that point it beeps and stops moving.

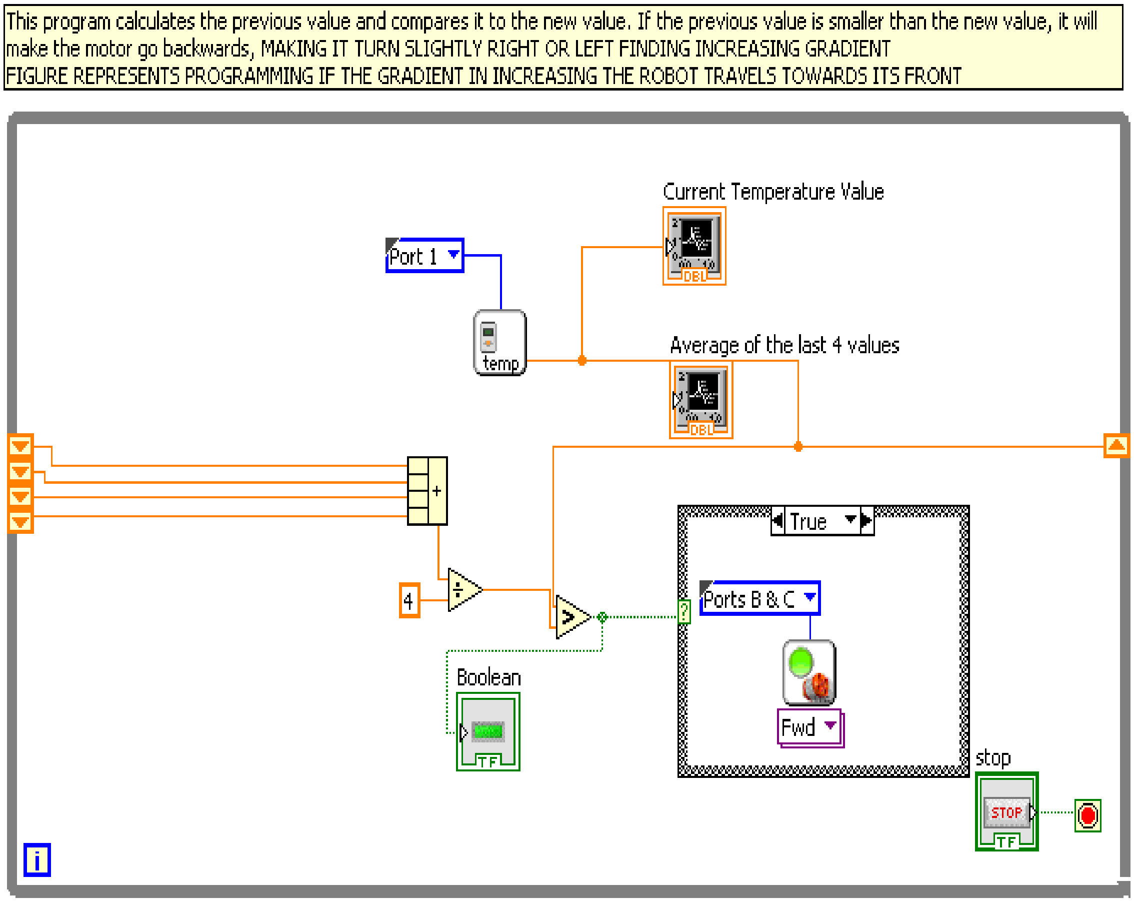


Figure 5. 6 LabVIEW programming for a while loop with shift register showing the true case of increasing gradient of object temperature

As it can be seen from the simple programming that the TIR sensor is connected to the brick via port 1. There are two charts produced by this program. One shows the current raw value of temperature detected by the sensor in degree Celsius and the other chart displays the average of the last four values of the temperatures to make the chart smoother. The case structure has the capability to return different values if a true or a false value is provided to it as input. The stop button terminates the program. It can also be connected to a specific situation as it is reached when the program may stop, such as the achievement of a high temperature to declare a fire incident.

As an increasing gradient of temperature is observed, a green LED lights up indicating the robot is travelling towards the source. This light goes off as either the gradient of heat is constant or has a decreasing trend.

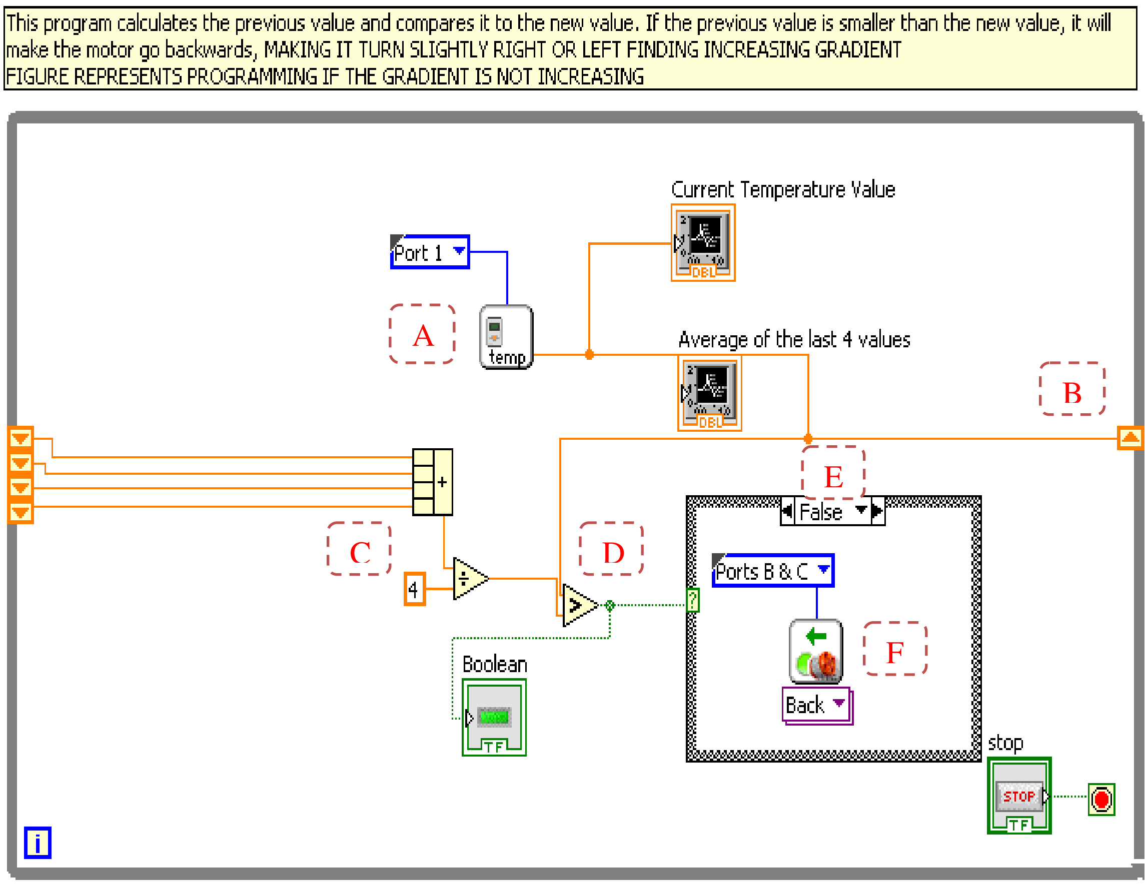


Figure 5. 7 LabVIEW programming for a while loop with shift register showing false case for increasing gradient of object temperature

Several experiments were performed to check the validity of the success of the program with good results. It was observed that the robot reached the source every time as long as the source had a noticeable temperature gradient difference for the sensor to detect.

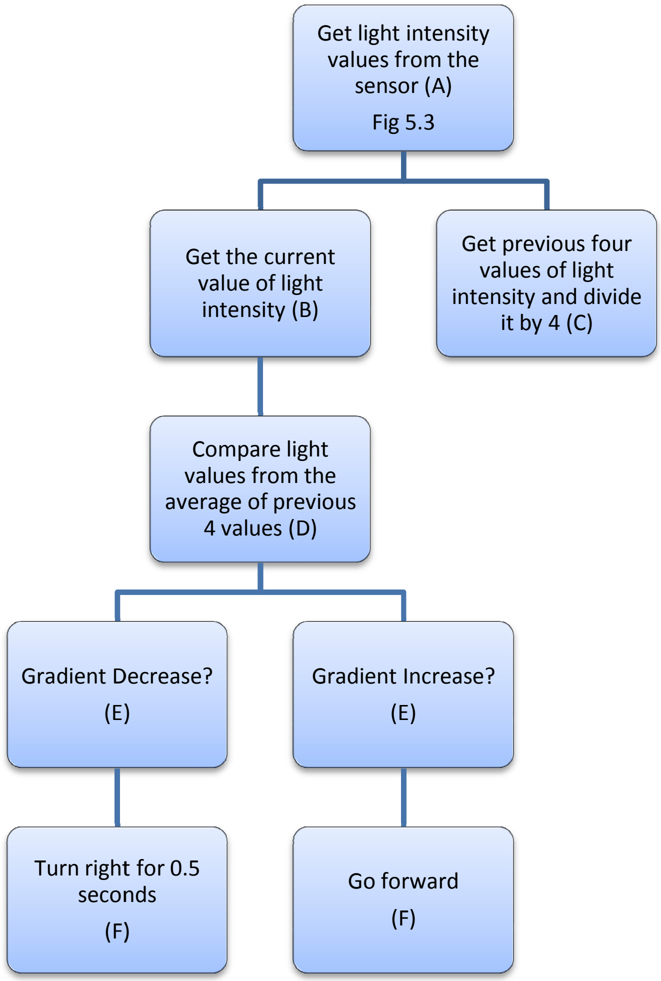


Figure 5. 8 Block diagram for one sensor gradient increase VI

In this particular experiment the robot was placed in the plain sight of the source without any obstacles in the way. Hence the obstacle avoidance techniques were not used. The speed of the robot was kept at 50% to allow enough time to detect the temperature and not miss readings.

The waiting time for each reading was one tenth of a second, way below the sensor capacity to make sure that the sensor does not return an indefinite value.

As evident from Figure 5.5, the robot continuously followed the increased gradient of temperature until it reached a peak value of 130°C, which had been pre-defined as the declaration of fire.

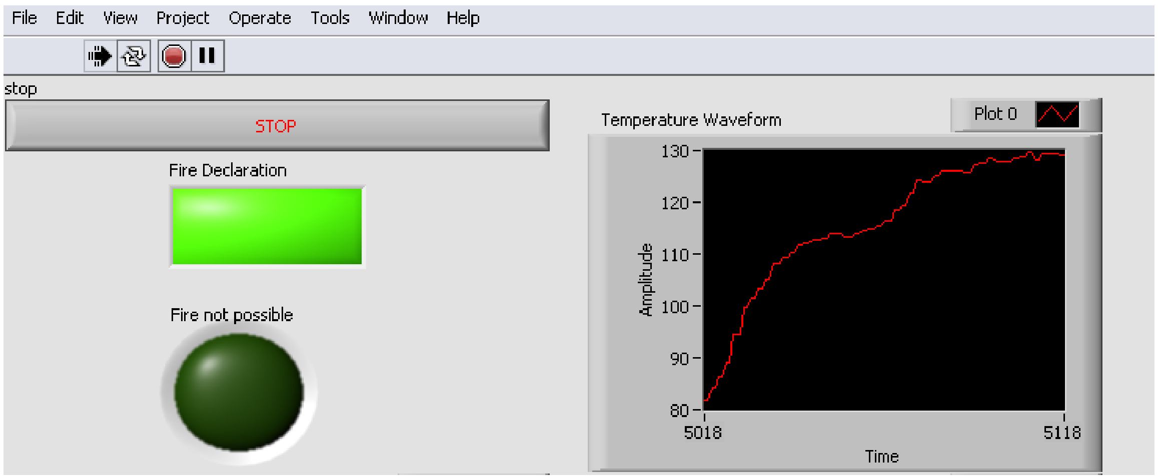


Figure 5. 9 Temperature waveform for the single sensor based increasing gradient trail guidance

If the waveform was to be looked at critically it can be observed that there are some points in the curve where the temperature was steady for a brief moment of time such as at 95°C and 126°C. Also another observation could be made for the temperature actually reducing at 114°C, 128°C and 120°C. but other than these points the gradient followed is always increasing.

Also from 80°C to 95°C the curve is exponential which at a constant speed signifies that the robot was traveling straight towards the heat source. When the reflected temperatures come into effect as the robot approaches closer to the source it can be observed that the robot had to correct its direction to find the highest possible value in its area of scanning. It took the robot 10 seconds to reach the goal.

Certain amplitudes and frequencies were tested and a mean value was reached that produced accurate detection of the source (giving enough time to the sensors to track the light source) while not exhausting the batteries at a faster rate.

Tangents were drawn at 45˚ on the chart to find out that the actual area covered was 180˚. Moving in the sinusoidal movement not only eliminates the chances of the robot travelling to a point that is reflecting the signal in question but also makes sure that other sources are also kept under consideration.

5.3 Tracking of the source with TWO sensors

Tracking of a light source with two sensors gives us an opportunity for a strategy of a continuous comparison between the sensor readings is and, depending upon the sensor reading values, for a robot control that can change its direction of movement.

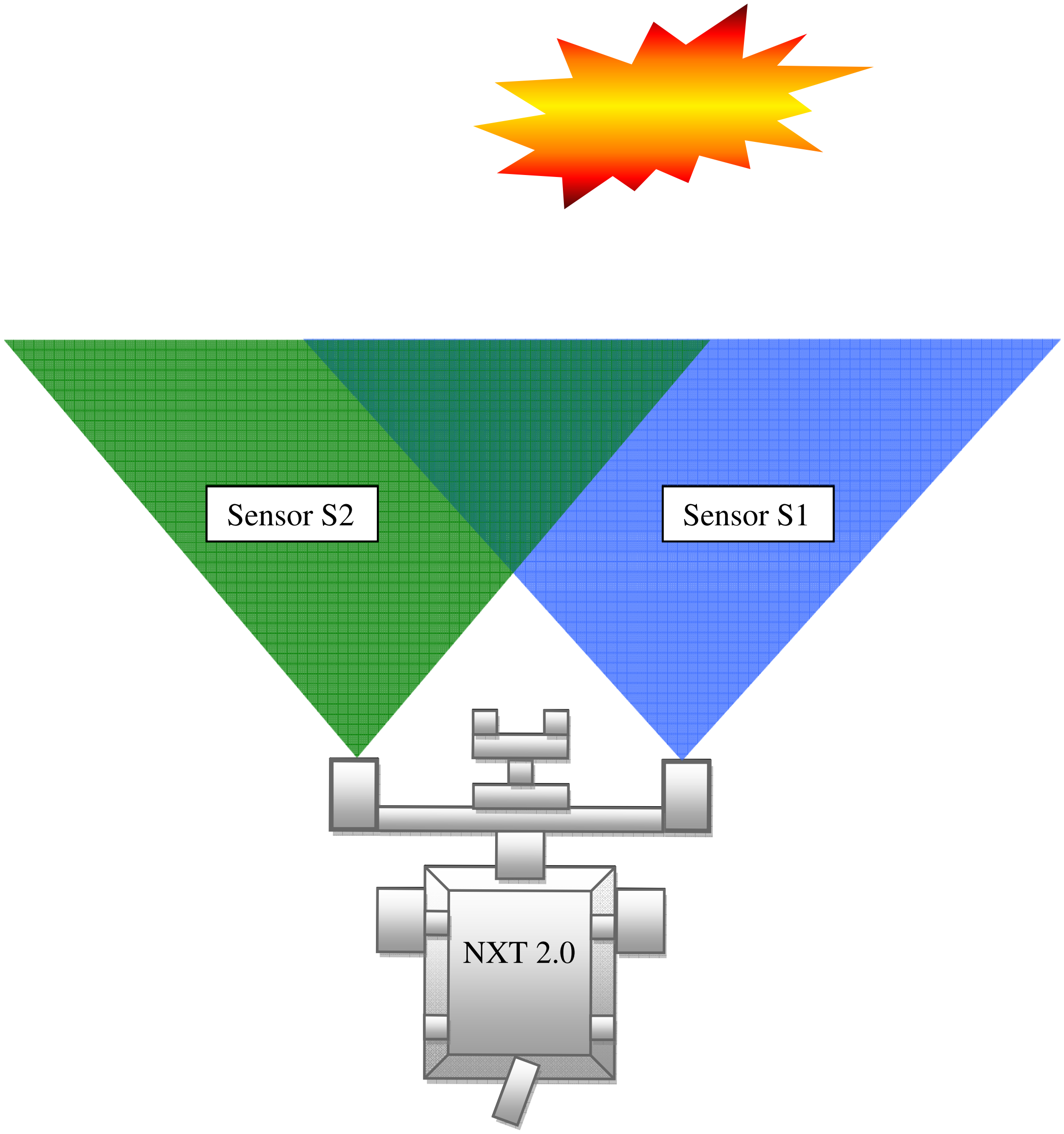


Figure 5. 10 Two light-sensor tracking system

Essentially the two sensor readings are compared by using a comparison operator. In Figure 5.6 the peripheral visual range of the sensors is described but the ambient and reflected light does reach the sensor as well. The robot successfully reaches the source by repeating the commands until a termination condition such as a stop button or intensity of light above a certain value is reached.

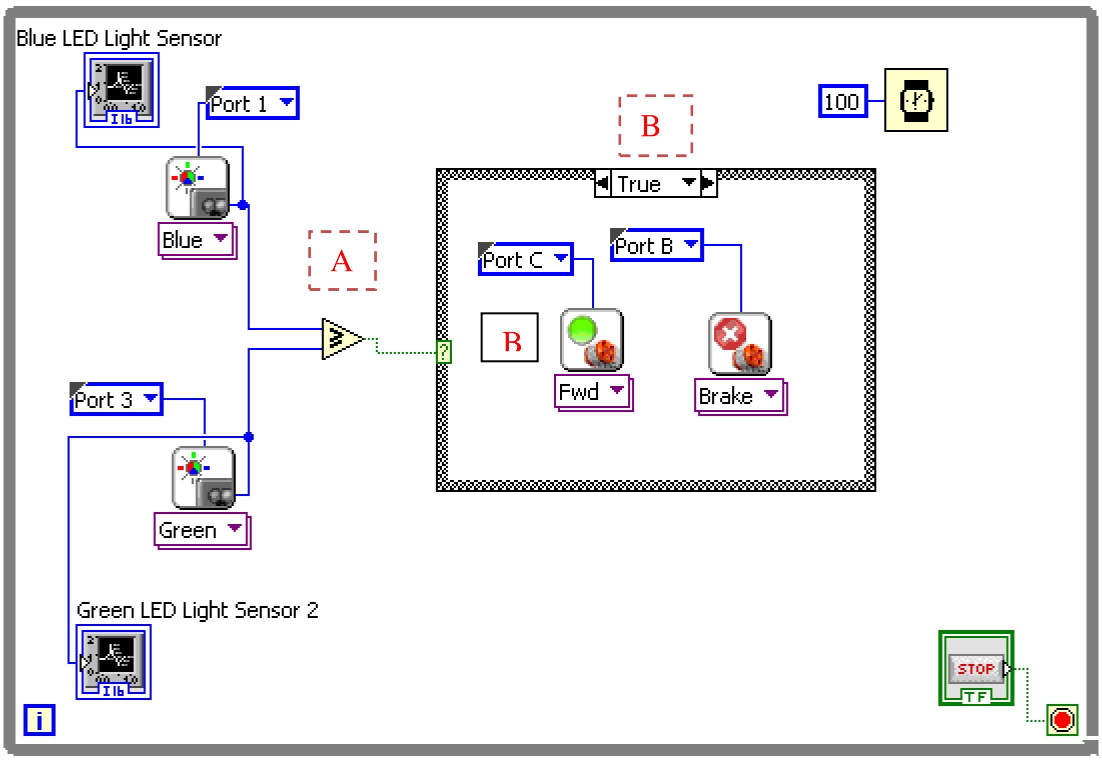


Figure 5. 11 VI for two sensor source approaching

As the two sensors are connected to two different ports, they are defined by the color of light their lamp emits and the position of port they are connected to. The motors are also defined by the name of port they are connected to. For data acquisition two charts are also connected to the raw data so that the observer can log the data. For the comparison operator, a greater or equal operator is used. The reason for this operator being used is that if the readings of both sensors at any given scenario are equal, the robot moves and creates an unequal reading from these sensors hence avoiding indeterminate points while approaching the source of light.

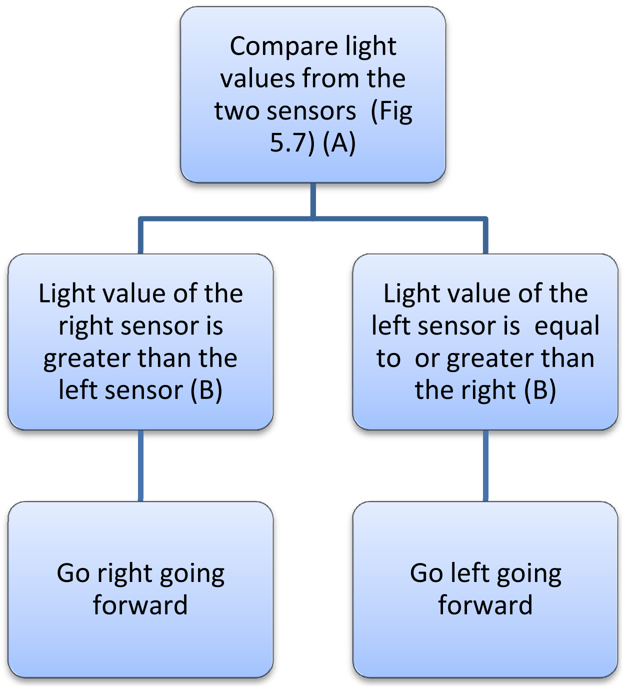


Figure 5. 12   Block diagram for two-sensor light following

The front panel from Fig. 5.10 of this virtual instrument (VI) gives a graphical representation of the approach towards the light.

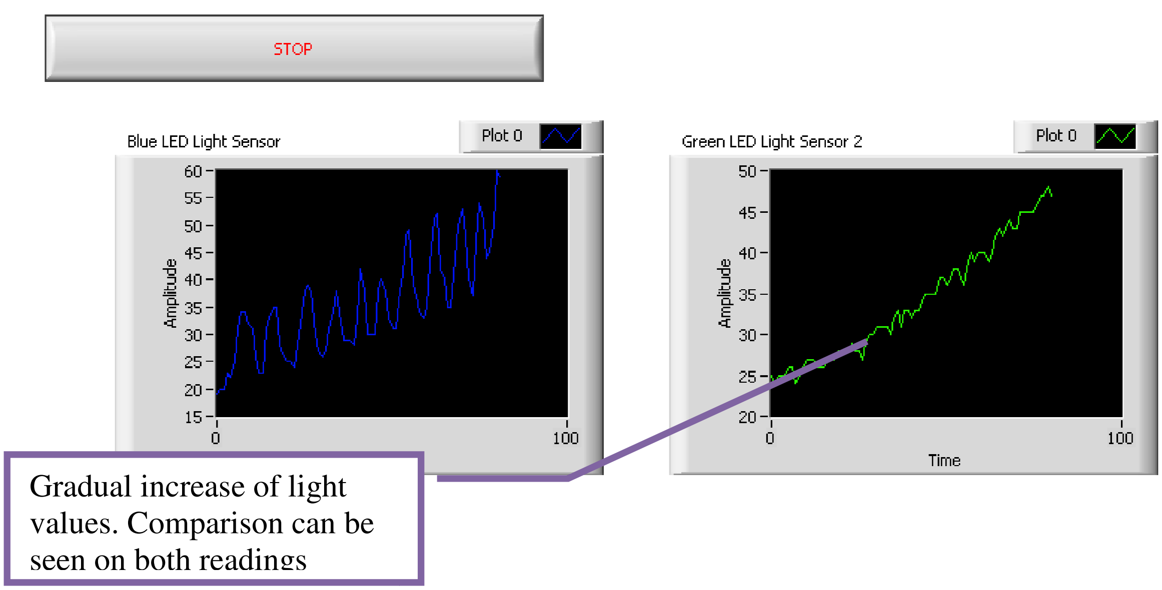


Figure 5. 13   Front Panel for two-sensor light tracking system

Figure 5.8 shows the sensor readings as the robot travels in a zigzag motion leaning towards a higher gradient of light and finally approaching it. For this experiment the robot was placed in a dark room with one light source while it detected and approached it.

5.4 Obstacle Avoidance

One of the major ingredients of a robot program is obstacle avoidance. This is particularly necessary for the robot to be in a good shape to perform different actions.

SONAR or Ultrasonic sensor was used for obstacle avoidance in these experiments. Simple avoidance would consist of three steps

- Scan the area for any obstacles
- When an obstacle is detected within a pre-defined distance, either change direction or back up
- Continue to scan for variables of interest after performing these actions.

In the current deployment of the VI's it was important that the robot does not waste time in trying to figure out which way to turn hence the two light sensors on either side help the robot making a choice of direction to back up too.

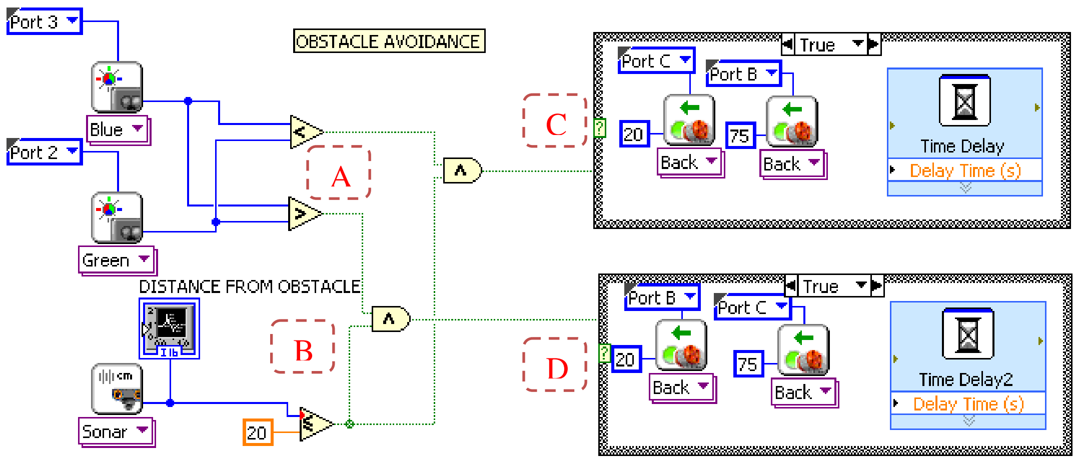


Figure 5. 14 Intelligent obstacle avoidance keeping into account the direction of backing up

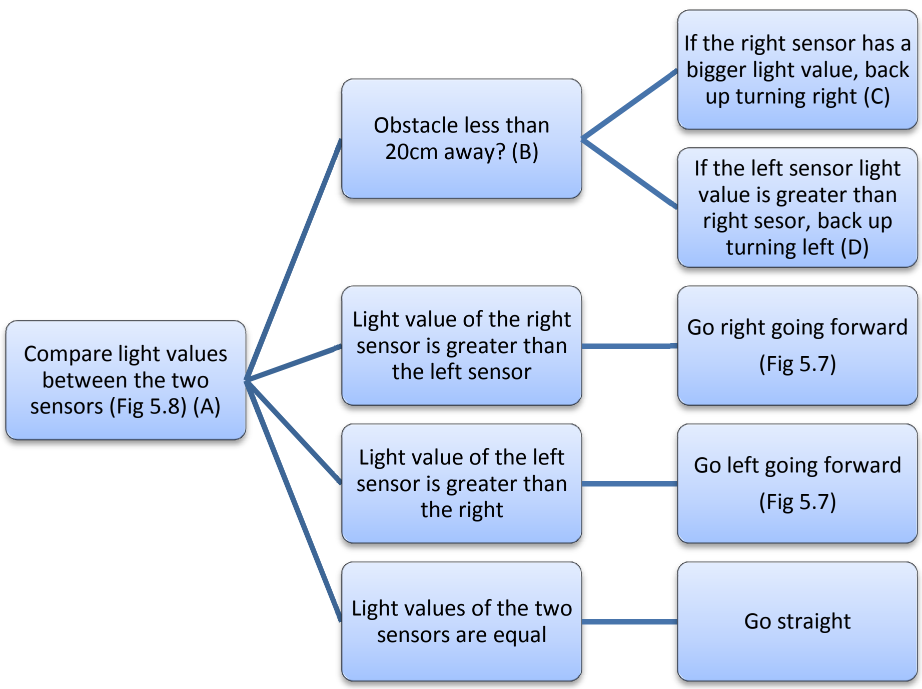


Figure 5. 15 Block diagram for obstacle avoidance

As the robot approaches an obstacle the ultrasonic sensor S4 comes into control of the motors. At this point the robot would back up not going straight backwards but detects the light values from the two light sensors.

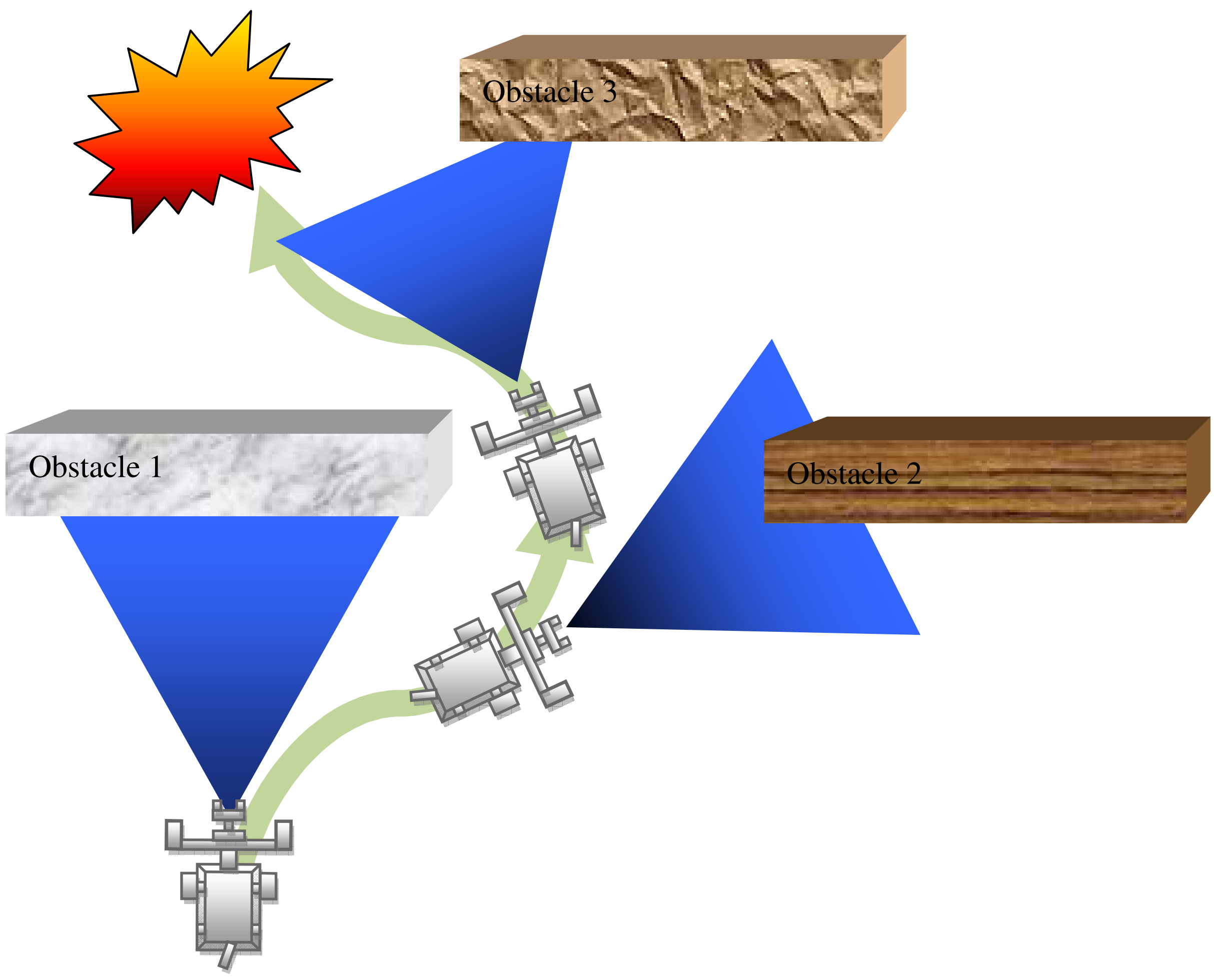


Figure 5. 16 Obstacle Avoidance

If Sensor S1 receives a higher value of light than the sensor S2, it would back up turning towards the direction of the sensor S1 and if the sensor S2 is displaying a higher reading, it would turn towards the direction while backing up, towards the sensor S2.

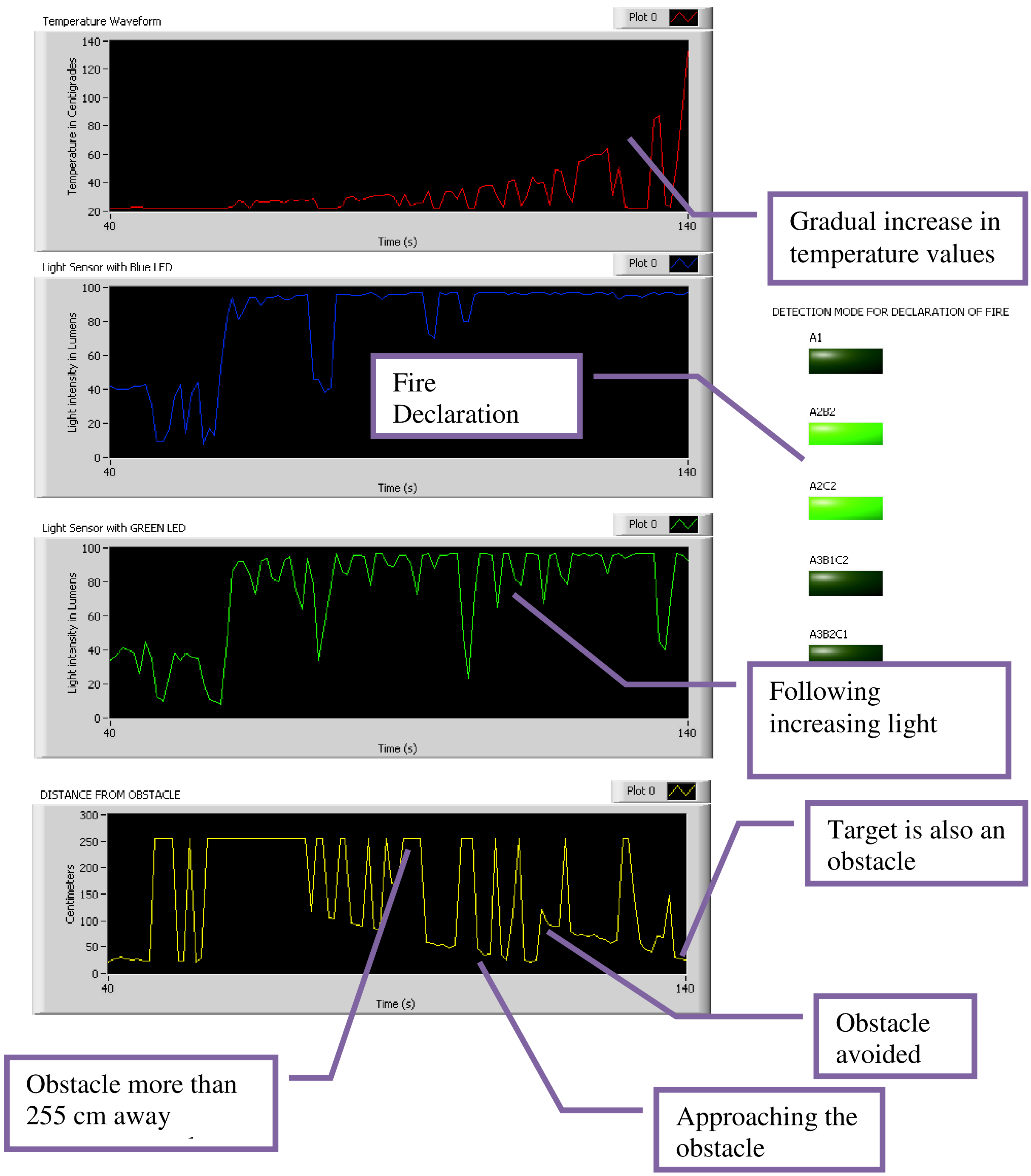


Figure 5. 17 Front panel results for obstacle avoidance with record of temperature readings

Chapter 6
Voting Logic Fusion

6.1 Introduction

As evident from its name, Voting Logic Fusion is a sensor fusion technique that takes all the sensors and their level of readings into account in the source declaration process. It is a very useful technique to detect, track and classify objects. This technique provides superior protection against false alarms in a high clutter or noisy background. A detailed description of this technique is given in the book "Sensor and Data Fusion: A Tool for Information Assessment and Decision Making" by Lawrence A Klein [18] .

Different sensor arrangements have different advantages and disadvantages. For example a parallel configuration of the sensors means that each sensor is working independently and the decision making process does not depend on other sensors readings. This arrangement is especially very efficient in detecting the suppressed or noisy targets. For this sensor arrangement, extra care must be taken to choose the sensors as it requires sophisticated and accurate sensors, increasing the cost of the assembly. Also this type of arrangement is susceptible to false alarms, as at one time only one sensor is responsible for declaration of the targets. Hence it is easy to distract a robot with this type of sensor arrangement.

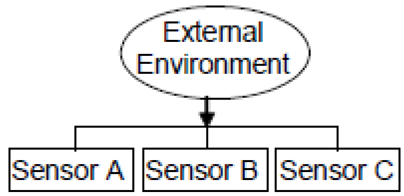


Figure 6. 1 Parallel sensor arrangement [18]

Venn Diagram for the parallel arrangement appears to be as follows:

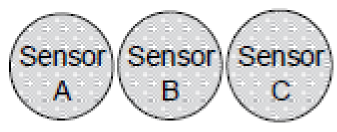


Figure 6. 2 Venn diagram for parallel sensor arrangement [18]

Series configuration, on the other hand requires all the sensors to declare a target simultaneously for the system to announce declaration. The advantages of this system are reverse of the parallel configuration. This configuration is very good in rejecting false alarms from decoys but on the other hand this system does not exhibit a good suppressed target declaration. This configuration does not require extremely high quality sensors hence the cost of the system is low.

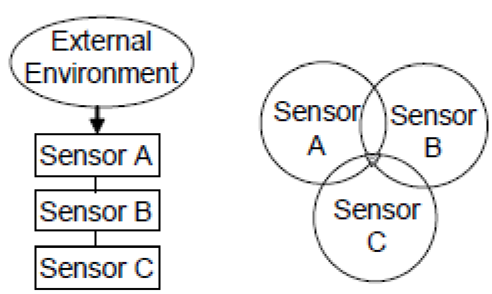


Figure 6. 3 Series sensor arrangement with Venn diagram[18]

It can be seen from the Venn diagram that the detection area, shaded in grey, does not cover a large area hence declaration of the target is difficult as this configuration will only allow declaration when all sensors are detecting the target.

It is expected that a combination of both of these configurations would produce a product that is more efficient, while detecting suppressed targets and is not susceptible to false alarms. The series/parallel configuration does just that (Fig. 6.4).
This configuration is not only able to detect suppressed targets but also is able to reject decoys. It is also particularly better than the first two configurations when it comes to noisy signals coming from the target. On the other hand, it does increase the complexity of the declaration system.

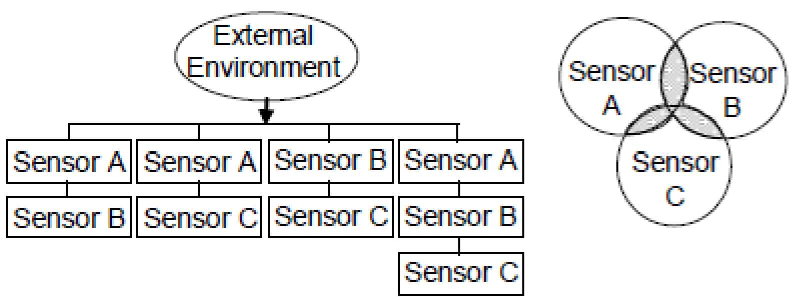


Figure 6. 4 Series/Parallel configuration of sensor arrangement [18]

The shaded area describes the declaration space in the Venn diagram. The different combinations of sensor readings, such as AB, AC, BC and ABC, can be seen. If the sensor readings lie in any of these combinations, a target is declared.

This type of sensor arrangement supports a Voting Logic Fusion process. In this process, the user gets the best of both the worlds. It allows the sensors to automatically detect and classify targets based on the knowledge gained by sensing. This process also does not require manual switching of the sensors based on the quality of their inputs rather this system has the ability to understand different levels of signatures in different combinations. This configuration may also be modified to suit the needs of another current project. Some predefined conditions may also be added in the rules of declarations.

The fusion algorithm combines the target report data and assesses the likelihood of the target being present at any location. The characteristics of the sensor inputs such as spatial frequency, amplitudes and bandwidth play a significant role in fusion algorithm.

6.2 Confidence Levels

Each sensor has a degree to which the signal conforms to pre-defined target characteristics. The amount to which an output signal complies with the pre-defined characteristics of the potential target, determines the confidence level of the sensor report. The confidence level is dependent not only on the sensor qualities but also the target characteristics. So it can be said that the confidence level is dependent on the degree of which an input signal matches an ideal target, the pre-identified value that matches to the ideal target and signal to interference ratio.

The confidence levels are highly dependent on the quality of the sensors such as whether the sensor is active or passive, its spectral band, resolution and its field of view. The following table describes the different characteristics of the sensors and their dependence on targets.

Feature Category	Representative Features	Other Attributes
Geometrical	Edges, lines, line widths, line relationships (e.g., parallel, perpendicular), arcs, circles, conic shapes, size of enclosed area	Represents the geometric size and shape of objects Man-made objects tend to exhibit regular geometric shapes with distinct boundaries
Structural	Surface area; relative orientation; orientation in vertical and horizontal ground plane; juxtaposition of planes, cylinders, cones	Develops a larger scale and contextual view of image segments
Statistical	Number of surfaces, area and perimeter, moments, Fourier descriptors, mean, variance, kurtosis, skewness, entropy	Used at local and global image levels to characterize image data
Spectral	Color coefficients, apparent blackbody temperature, spectral peaks and lines, general spectral signature	Man-made objects tend to possess distinct infrared spectral signatures

Table 6. 1 *Some representative features and other attributes of different types of targets* [19]

In this thesis the nomenclature that has been used for confidence levels is: low confidence, medium confidence and high confidence. These confidence levels are defined by the programmer. In this nomenclature, A_1 would be considered as the lowest confidence level, A_2 would be a medium confidence level and A_3 is the high confidence level. Later in the next chapter there has been an introduction of the confidence level A_4 which will be discussed in detail while examining the modification of the voting logic. Same nomenclature can be adopted for the other sensors with a subscript of the level of confidence.

6.3 Detection Modes

Detection modes may be defined as the combinations of sensor outputs that may be considered as the presence of a valid target declaration. In a typical detection mode the user may define a combination of the lowest confidence level detected by all the sensors detecting the target, or it may include one sensor with high confidence level and two with intermediate or low confidence levels.

In a three-sensor detection system, if the sensor nomenclature was to be considered as A, B and C and the confidence levels are defined as subscript 1 for the lowest and 3 for the highest confidence level, the combinations that are attained are discussed in table 6.2.
As it can be clearly seen from the combinations that a variety of possible combinations is present and the combinations of interest may only be defined by the user as deciding combinations for declaration of the target.

There are 27 i.e., (3^3 or 3x3x3) combinations for the three sensor system with three confidence levels as described in Table 6.2. They range from the lowest confidence levels to the highest confidence levels.

Also Tables 6.3, 6.4 and 6.5 detail the possible combinations for the two sensor combinations. Nine possible combinations i.e. (3^2) describe detection modes for two sensor combination.

Out of these possible combinations detection modes may be defined. For example if a detection mode for three sensors is to be defined as a combination of at least low confidence level reading from all these sensors may be considered to be a detection mode. Also for two sensor combinations, at least medium confidence from both of the sensors may be defined as a possible detection mode. In different cases different combinations are required for detections.

Combination of sensors	Possible combinations of confidence levels
ABC	$A_1B_1C_1$ $A_1B_1C_2$ $A_1B_1C_3$ $A_1B_2C_1$ $A_1B_2C_2$ $A_1B_2C_3$ $A_1B_3C_1$ $A_1B_3C_2$ $A_1B_3C_3$

	$A_2B_1C_1$ $A_2B_1C_2$ $A_2B_1C_3$ $A_2B_2C_1$ $A_2B_2C_2$ $A_2B_2C_3$ $A_2B_3C_1$ $A_2B_3C_2$ $A_2B_3C_3$ $A_3B_1C_1$ $A_3B_1C_2$ $A_3B_1C_3$ $A_3B_2C_1$ $A_3B_2C_2$ $A_3B_2C_3$ $A_3B_3C_1$ $A_3B_3C_2$ $A_3B_3C_3$

Table 6. 2 Three sensor combinations when all sensors inputs are obtained

Combination of sensors	Possible combinations of confidence levels
AB	A_1B_1

	A_1B_2 A_1B_3 A_2B_1 A_2B_2 A_2B_3 A_3B_1 A_3B_2 A_3B_3

Table 6. 3 Two sensor combinations for sensors A and B

Combination of sensors	Possible combinations of confidence levels
AC	A_1C_1 A_1C_2 A_1C_3 A_2C_1 A_2C_2 A_2C_3 A_3C_1 A_3C_2 A_3C_3

Table 6. 4 Two sensor combinations for sensors A and C

Combination of sensors	Possible combinations of confidence levels
BC	B_1C_1 B_1C_2 B_1C_3 B_2C_1 B_2C_2 B_2C_3 B_3C_1 B_3C_2 B_3C_3

Table 6. 5 Two sensor combinations for sensors B and C

These choices highly depend upon the inherent qualities of the sensors. So in a typical case where sensor A has a higher probability of detection, the confidence level of sensor A required to declare a target may not require the highest possible level when in combination with other sensors. An example of the declaration modes is provided in the following table 6.6

Mode	Sensor and Confidence Level		
	A	B	C
ABC	A_1	B_1	C_1
AC	A_2	-	C_2
BC	-	B_3	C_3
AB	A_3	B_3	-

Table 6. 6 Confidence levels in a three-sensor system declaring detection modes

Table 6.6 describes the detection modes that can declare the presence of a target and the combinations of the minimum confidence levels for declaration. So in the above table the expression can be written as the detection modes of $A_1B_1C_1$ or A_2C_2 or B_3C_3 or A_3B_3. It is important now to calculate the probability of detection for the above system

6.4 Detection Probability

At this point it is important to establish the probability of detection and false alarm based on the sensor confidence levels and ratios of signal-to-noise and target fluctuation observed by each sensor.

6.4.1 Derivation of system detection and false-alarm probabilities

Using these confidence level combinations (detection modes) Boolean algebra may be used to derive the system detection and system false-alarm probabilities. As described in the previous section, there are one three-sensor and three two sensor detection modes. The system probability would be the sum of the individual probabilities of each detection mode. As an illustration, based on the expert knowledge of the designer, it will be considered the following logic combination

$A_3B_3C_3$ OR A_2C_2 OR B_1C_1 OR A_1B_1

gives the equation for system probability of detection

$$\text{System } P_{d} = P_d\{A_3B_3C_3 \text{ OR } A_2C_2 \text{ OR } B_1C_1 \text{ OR } A_1B_1\} \qquad (6.1)$$

This equation may be expanded by repeated application of the Boolean algebra expression given as

$$P\{X \text{ OR } Y\} = P\{X\} + P\{Y\} - P\{XY\} \qquad (6.2)$$

The equation 6.1 then gets expanded as follows

$$\begin{aligned}\textbf{System P}_{\boldsymbol{d}} = {} & P_d\{A_3B_3C_3\} + P_d\{A_2C_2\} + P_d\{B_1C_1\} + \\ & P_d\{A_1B_1\} - P_d\{A_3B_3C_1A_2C_2\} - P_d\{A_3B_3C_3B_1C_1\} - \\ & P_d\{A_3B_3C_3A_1B_1\} - P_d\{A_2B_2B_1C_1\} - P_d\{A_2C_2A_1B_1\} - \\ & P_d\{B_1C_1A_1\} + P_d\{A_3B_3C_3A_2C_2B_1C_1\} + \\ & P_d\{A_3B_3C_3A_2C_2A_1B_1\} + P_d\{A_3B_3C_3B_3C_1A_1B_1\} + \end{aligned} \qquad (6.3)$$

$P_d\{A_2C_2B_1C_1A_1B_1\} + P_d\{A_3B_3C_3A_2C_2B_1C_1A_1B_1\}$

These are non-nested sensors so the confidence levels of each sensor is independent of others, hence the expression for union and intersection that are applicable are as follows:

$$P_d\{A_1 \cup A_2\} = P_d\{A_1\} + P_d\{A_2\} \tag{6.4}$$

And

$$P_d\{A_1 \cap A_2\} = 0 \tag{6.5}$$

Hence the simplified system detection probability expression becomes:

$$\textbf{System } \mathbf{P_d} = P_d\{A_3B_3C_3\} + P_d\{A_2C_2\} + P_d\{B_1C_1\} + P_d\{A_1B_1\} - P_d\{A_1B_1C_1\} \tag{6.6}$$

As each sensor is independent of the readings of the other sensors, the probability of detection may be written as the product of the probability of detection from each sensor. This yield:

$$\textbf{System } \mathbf{P_d} = P_d\{A_3\}\, P_d\{B_3\}\, P_d\{C_3\} + P_d\{A_2\}\, P_d\{C_2\} + P_d\{B_1\}\, P_d\{C_1\} + P_d\{A_1\}\, P_d\{B_1\} - P_d\{A_1\}\, P_d\{B_1\}\, P_d\{C_1\} \tag{6.7}$$

Equation 6.7 describes the total system probability of detection as the product of the detection probabilities of sensors A, B and C at the lowest confidence level added to the product of probability of detection of the sensors A and B at the medium confidence levels added to the product of probability of detection of sensors A and C at the highest confidence level, subtracted by the product of detection probabilities of sensors A, B and C at the highest confidence level.

Meanwhile as each system has a false alarm probability, it is as important to calculate the false alarm probability as it is to calculate the detection probability. The same equation, (Equation 6.7) may be used to detect false alarm probability of the system as well. [18]

$$\textbf{System } \mathbf{P}_{fa} = \mathrm{P}_{fa}\{A_3\}\,\mathrm{P}_{fa}\{B_3\}\,\mathrm{P}_{fa}\{C_3\} + \mathrm{P}_{fa}\{A_2\}\,\mathrm{P}_{fa}\{C_2\} + \mathrm{P}_{fa}\{B_1\}\,\mathrm{P}_{fa}\{C_1\} + \mathrm{P}_{fa}\{A_1\}\,\mathrm{P}_{fa}\{B_1\} - \mathrm{P}_{fa}\{A_1\}\,\mathrm{P}_{fa}\{B_1\}\,\mathrm{P}_{fa}\{C_1\} \tag{6.7}$$

Where "System P_{fa}" is the false alarm probability of the system.

6.4.2 System detection probability

Using the values from three sensors, two of which are light and color sensors, and one of them is temperature sensor. The individual sensor detection probability at a particular confidence level is calculated by multiplying the inherent detection probability of that sensor by the conditional probability. Then the modal detection probability is calculated by multiplication of sensor detection probabilities

These are the steps to follow while computing the detection probability

- Determination of the detection modes
- Selection of inherent false alarm probabilities for each sensor confidence level
- Calculation of the conditional probabilities corresponding different confidence levels by performing offline experiments.
- Calculation and verification of false alarm probabilities
- Calculation of the inherent false alarm probabilities of each sensor
- Calculation of the inherent detection probabilities of each sensor
- Calculation of the probabilities of target detection by each sensor at appropriate confidence level
- Computation of system detection probability
- Computation of system false alarm probability
- Verification of the satisfaction of the requirements

Chapter 7
Modified Voting Logic Fusion

7.1 Introduction:

Voting logic, as described in Chapter 6, is the process of declaration of a source that keeps into account the values, confidence levels and algorithms of all participating sensors. This system has great deterrence against non detection and false alarms. In order to improve on the currently available voting logic system, there are certain modifications that may be made. Even though this system exhibits a great flexibility, there is still the possibility of non-detection and false alarm.

Depending upon the type of sensors, certain logic rules may be implemented that are necessarily not part of voting logic to use these sensors more efficiently.

7.2 Single Sensor Detection Modes

The current thesis focuses on fire detection in an industrial environment. Fire exhibits certain qualities that may be clues for declaration of a fire source. Some of these variables are more important part of declaration process than others. For example a fire would

- Sometimes generate smoke
- Most often generate light

- Always generate heat
- Always produce CO_2

The presence of only smoke or light may not be enough evidence to declare fire. Also CO_2 is normally found in the atmosphere and the fire may not be the only source to produce that gas if elevated levels of Carbon Dioxide are detected. That could be because of people breathing in a closed environment or a manufacturing process.

Heat, on the other hand, if above certain threshold, maybe enough evidence of a threatening situation provided there are no controlled fires present in that area, such as a forging shop or a heat treatment shop. In heat treatment shops normally the temperatures are inside the kiln and outside temperatures are normal.

Therefore it is fitting to include the singleton sensor detection modes in fire declarations for the industrial environment[11] Current hardware did not allow the use of smoke or CO_2 sensors so two light sensors and one heat sensor was used in the first batch of experiments.

A fire declaration is possible in the current circumstances when we have the light readings above threshold and the temperature above a certain level. The possibility of fire diminishes if the light sensors are providing a reading that is higher but the robot does not detect elevated temperatures. The robot may reach close to the target where due to robot geometry the light sensors may not give a reading that falls in any confidence level but it has approached the source. At that instance the sensor A will give the highest confidence level due to the temperature present but since the other sensors are not able to sense it, voting logic will not declare a target based on the output of just one sensor.

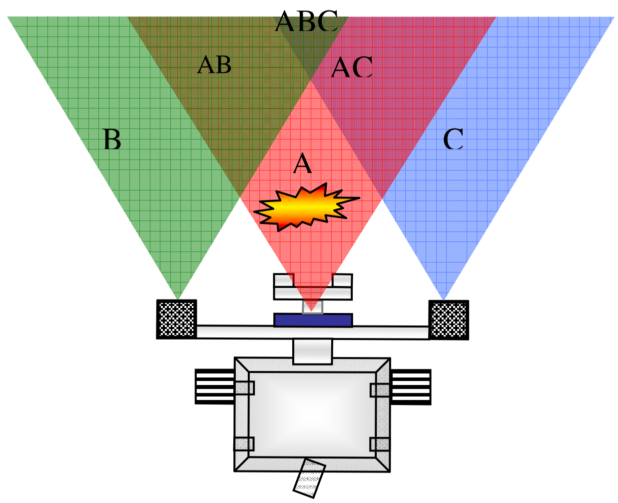


Figure 7. 1 Possible combinations of sensor readings

At this point the reading from the other sensors becomes irrelevant. Normal voting logic does not keep this scenario into account. Whereas in order to reach the point of interest the robot has to follow any lead of increased light only and will not declare the fire source until it reaches a point where elevated temperatures are also detected.

Hence single sensor detection mode was introduced in this chapter which marks one modification of the mode. In the following in this thesis, sensor A, as described by the temperature sensor (TIR), the confidence level A_1 will always declare fire, as it may be the deciding factor due to robot geometry or type of fire. As an illustration, based on the expert knowledge of the designer, it will be considered the following logic combination of the detection modes ehich gives the following equation for system

$$A_1 \text{ or } A_2B_2 \text{ or } A_2C_2 \text{ or } A_3B_1C_2 \text{ or } A_3B_2C_1 \quad (7.1)$$

7.2.1 Visual Representation of these detection modes

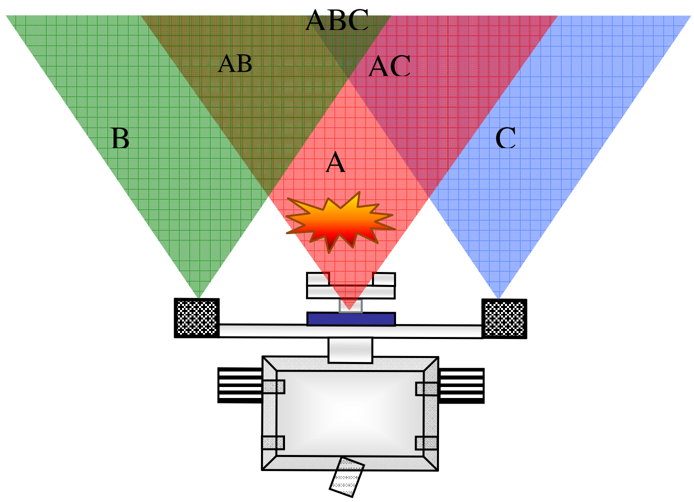


Figure 7. 2 Fire present at First detection mode A_1

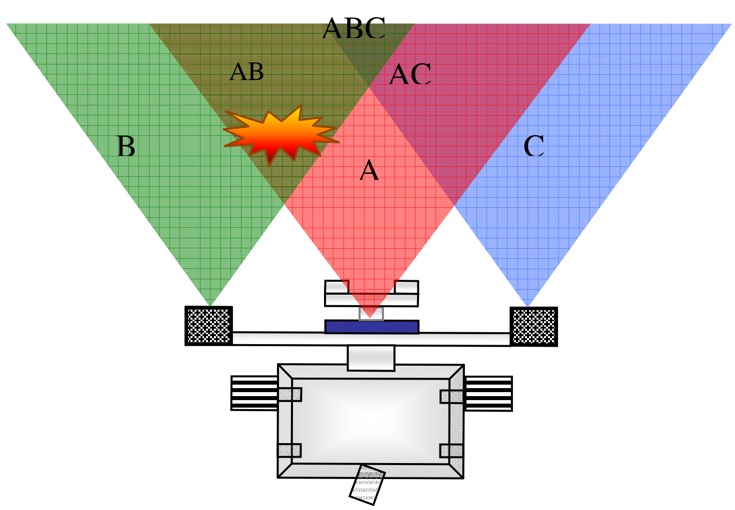


Figure 7. 3 Fire present at First detection mode A_2B_2

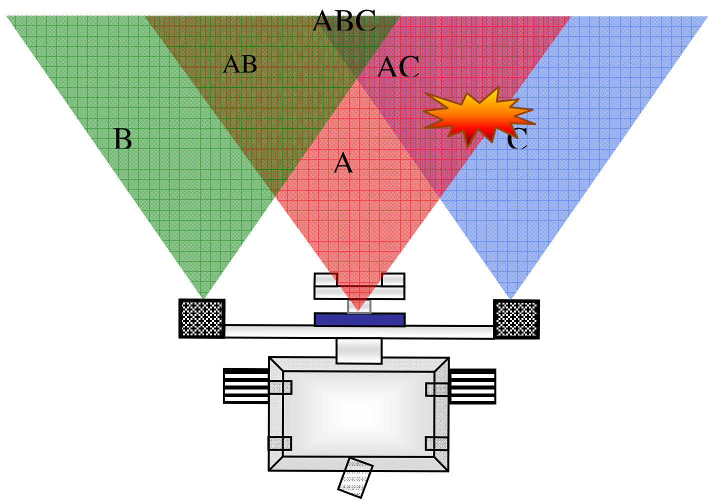


Figure 7. 4 *Fire present at First detection mode* $\boldsymbol{A_2C_2}$

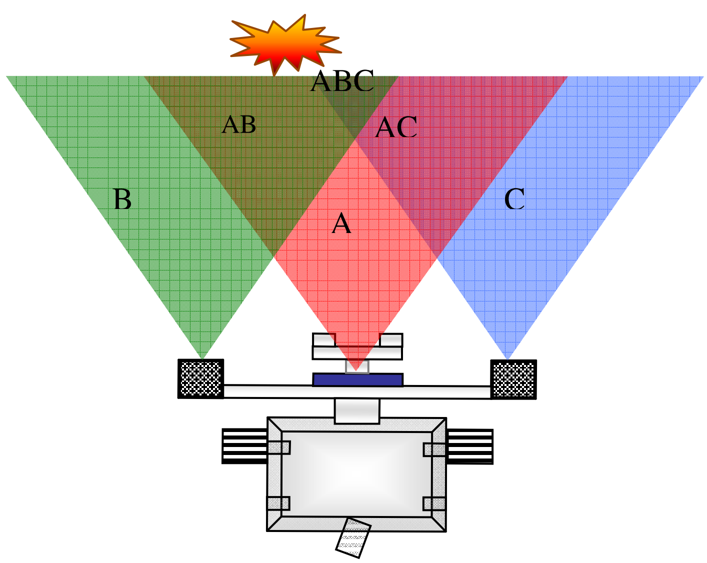


Figure 7. 5 *Fire present at First detection mode* $\boldsymbol{A_3B_1C_2}$

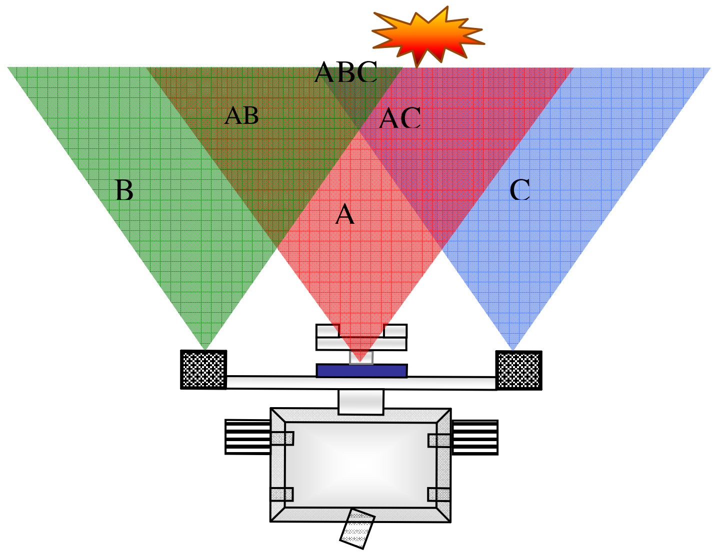


Figure 7. 6   Fire present at First detection mode $A_3B_2C_1$

7.2.2 Single Sensor Non-Possibility Mode

As in section 7.2 different detectable fire characteristics were described, one of which is that it is not possible to have a fire while the temperatures are low. There could be a presence of light, Carbon Dioxide, smoke but if there is no heat present, it can be safely said that there is no fire present, as smoke and CO_2 may have been generated from other processes and light is always present in any workshop.

Hence it is also fitting to say that a single sensor may not only be a deciding factor in a declaration but also the same sensor may imply that a fire occurrence is not possible., as clear from the name, single sensor non possibility mode. In this case the algorithm will ignore any combination of detection probabilities while elevated temperatures are not detected.

In the description to follow, the confidence level introduced as A_4 will declare the non-possibility of fire.

The nomenclature for the subscript numbers for sensor A are:

A_1 = Highest confidence (Single sensor declaration level confidence)

A_2 = High confidence

A_3 = Medium confidence

A_4 = Low confidence (Single sensor non-declaration level confidence)

The reason for adoption of this nomenclature even though, different from the one provided in the previous chapter is the introduction of A_4, the non-possibility confidence level.

The significance of this single sensor non-possibility mode becomes more practical where there is a need to reduce calculation pressure on a CPU while there are many other combinations that it has to compute, all the combinations with single sensor non possibility mode may be ignored, increasing the efficiency and performance of the CPU. It is also a very practical solution for a limited capability robot that may increase its performance.

7.2.3 Derivation of Single Sensor System P_d

Equation 6.1 can be used to describe the Probability of detection of a sensor system. As we have a different combination of detection modes in this case, the equation can be modified to become

$$\text{System } P_d = P_d\{ A_1 \text{ or } A_2B_2 \text{ or } A_2C_2 \text{ or } A_3B_1C_2 \text{ or } A_3B_2C_1\} \quad (7.2)$$

A point to be noted here is that there is no combination having A_4 present, which automatically declares the non-possibility of the declaration of fire.

This equation may be expanded by repeated application of the Boolean algebra expression given as

$$P\{X \text{ OR } Y\} = P\{X\} + P\{Y\} - P\{XY\} \quad (6.2)$$

The equation 7.1 then gets expanded as follows

$$\begin{aligned} \textbf{System } \mathbf{P}_{\boldsymbol{d}} = {} & P_d\{A_1\} + P_d\{A_2B_2\} + P_d\{A_2C_2\} + P_d\{A_3B_1 C_2\} \\ & + P_d\{A_3B_2 C_1\} \\ & - P_d\{ A_1 A_2B_2\} - P_d\{ A_1 A_2C_2\}\} - P_d\{ A_1 A_3B_1 C_2\} - P_d\{ A_2B_2 A_2C_2\} \\ & - P_d\{ A_2B_2 A_3B_1 C_2\} - P_d\{ A_2B_2 A_3B_2 C_1\} - P_d\{ A_2C_2 A_3B_1 C_2\} \\ & - P_d\{ A_2C_2 A_3B_2 C_1\} - P_d\{ A_3B_1 C_2 A_3B_2 C_1\} \\ & + P_d\{ A_1 A_2B_2 A_2C_2\} + P_d\{ A_1 A_2B_2 A_3B_1 C_2\} + P_d\{ A_1 A_2B_2 \} \end{aligned} \quad (7.3)$$

$$+ P_d\{ A_2B_2\ A_2C_2\ A_3B_1\ C_2\} + P_d\{ A_2B_2\ A_2C_2 \} + P_d\{ A_2C_2\ A_3B_1\ C_2\ A_3B_2\ C_1\}$$

$$-P_d\{ A_1\ A_2B_2\ A_2C_2 \} - P_d\{ A_1\ A_2B_2\ A_2C_2\ A_3B_2\ C_1\}$$

$$- P_d\{ A_2B_2\ A_2C_2\ A_3B_1\ C_2\ A_3B_2\ C_1\} + P_d\{ A_1\ A_2B_2\ A_2C_2\ A_3B_1\ C_2\ A_3B_2\ C_1\}$$

These are non-nested sensors so the confidence levels of each sensor is independent of others, hence the expression for union and intersection that are applicable are as follows:

$$P_d\{A_1 \cup A_2\} = P_d\{A_1\} + P_d\{A_2\} \quad (6.4)$$

And

$$P_d\{A_1 \cap A_2\} = 0 \quad (6.5)$$

Hence the simplified system detection probability expression becomes:

$$\textbf{System } \mathbf{P_d} = P_d\{A_1\} + P_d\{A_2B_2\} + P_d\{A_2C_2\} + P_d\{A_3B_1\ C_2\} + P_d\{A_3B_2\ C_1\} \quad (7.4)$$

As each sensor is independent of the readings of the other sensors, the probability of detection may be written as the product of the probability of detection from each sensor. This yield:

$$\textbf{System } \mathbf{P_d} = P_d\{A_1\} + P_d\{A_2\}\ P_d\{B_2\} + P_d\{A_2\}\ P_d\{C_2\} \quad (7.5)$$

$+ P_d\{A_3\}\ P_d\{B_1\}\ P_d\{C_2\} + P_d\{A_3\}\ P_d\{B_2\}\ P_d\{C_1\}$

Equation 7.4 describes the total system probability of detection as the product of the detection probabilities of sensors A, B and C at the lowest confidence level added to the product of probability of detection of the sensors A and B at the medium confidence levels added to the product of probability of detection of sensors A and C at the highest confidence level, subtracted by the product of detection probabilities of sensors A, B and C at the highest confidence level.

The numerical values in tables 7.1-7.4 are assumed typical values just for illustrating the approach.

Meanwhile as each system has a false alarm probability, it is as important to calculate the false alarm probability as it is to calculate the detection probability. The same equation, (Equation 6.7) may be used to detect false alarm probability of the system as well. [18]

$$\textbf{System } \mathbf{P}_{fa} = P_{fa}\{A_1\} + P_{fa}\{A_2\}\ P_{fa}\{B_2\} + P_{fa}\{A_2\}\ P_{fa}\{C_2\} + P_{fa}\{A_3\}\ P_{fa}\{B_1\}\ P_{fa}\{C_2\} + P_{fa}\{A_3\}\ P_{fa}\{B_2\}\ P_{fa}\{C_1\} \quad (7.6)$$

Where “System P_{fa}” is the false alarm probability of the whole system after the algorithm is deployed.

Tables 7.1 to 7.9 contain illustrative numerical values for testing the how the proposed algorithms work.

Sensor Confidence Level	Sensor A				Sensor B			Sensor C		
	A_1	A_2	A_3	A_4	B_1	B_2	B_3	C_1	C_2	C_3
Detection distribution	350	550	800	1000	400	600	1000	400	600	1000
Conditional probability	0.35	0.55	0.8	1.0	0.4	0.6	1.0	0.4	0.6	1.0

Table 7. 1 Distribution of detections among sensor confidence levels

Inherent detection probabilities calculated for the sensors at the different confidence levels, as described in Equation 6.8

Sensor Confidence Level	Sensor A				Sensor B			Sensor C		
	A_1	A_2	A_3	A_4	B_1	B_2	B_3	C_1	C_2	C_3
Inherent Detection Probability	0.9	0.84	0.8	0.74	0.88	0.81	0.73	0.88	0.81	0.73

Table 7. 2 Inherent detection probabilities among sensor confidence level

To calculate the system probability of detection (System P_d), the values from the above tables are inserted in equation 7.5, which yields:

$$\textbf{System } \mathbf{P}_{d} = P_d\{A_1\} + P_d\{A_2\}\ P_d\{B_2\} + P_d\{A_2\}\ P_d\{C_2\} + P_d\{A_3\}\ P_d\{B_1\}\ P_d\{C_2\} + P_d\{A_3\}\ P_d\{B_2\}\ P_d\{C_1\} \tag{7.5}$$

$$\textbf{System } \mathbf{P}_{d} = 0.315 + (0.46 \times 0.486) + (0.46 \times 0.486) + (0.64 \times 0.352 \times 0.486) + (0.64 \times 0.352 \times 0.486) \tag{7.7}$$

$$\textit{System } P_d = 0.981$$

System detection probability at 98.1% is a valuable result, where the possibility of non-detection is less than 2%.

Similarly the calculations can be done for the false alarm probability of the system. Equation 7.6 provides the expression for false alarm calculations, as

$$\textbf{System P}_{fa} = P_{fa}\{A_1\} + P_{fa}\{A_2\}\ P_{fa}\{B_2\} + P_{fa}\{A_2\}\ P_{fa}\{C_2\} + P_{fa}\{A_3\}\ P_{fa}\{B_1\}\ P_{fa}\{C_2\} + P_{fa}\{A_3\}\ P_{fa}\{B_2\}\ P_{fa}\{C_1\} \tag{7.6}$$

Sensor Confidence Level	Sensor A			
	A_1	A_2	A_3	A_4
Inherent false alarm Probability ($P_{fa'}$)	1.06×10^{-4}	1.8×10^{-3}	1.4×10^{-3}	1.01×10^{-2}

Table 7. 3 Inherent false alarm probability for sensor A for all four confidence levels

Sensor Confidence Level	Sensor B			Sensor C		
	B_1	B_2	B_3	C_1	C_2	C_3
Inherent false alarm Probability($P_{fa'}$)	3.5×10^{-4}	2.0×10^{-3}	1×10^{-3}	3.5×10^{-4}	2.0×10^{-3}	1×10^{-3}

Table 7. 4 Inherent false alarm probabilities for sensors B and C

Taking the values from tables 7.3 and 7.4 into account, and using them to solve equation 7.6, the total system false alarm probability is obtained.

$$\textbf{System } \mathbf{P}_{fa} = (1.06\times10^{-4}\times0.9) + (1.8\times10^{-3}\times2.0\times10^{-3}) + (1.8\times10^{-3}\times2.0\times10^{-3})$$
$$+ (1.4\times10^{-3}) \times (3.5\times10^{-4}) \times (1 \times10^{-3}) + (1.4\times10^{-3}) \times (1 \times10^{-3}) \times (3.5\times10^{-4})$$

$$\textbf{System } \mathbf{P}_{fa} = (9.54 \times10^{-5}) + (4.32\times10^{-6}) + (4.32\times10^{-6}) + (4.9\times10^{-10}) + (4.9\times10^{-10})$$

$$\textit{System } P_{fa} = 1.0 \times10^{-4}$$

7.3 Two-sensor Detection and Non-Possibility Modes

Also depending upon the choice of sensors, if there were to be two heat sensors each of the two TIR sensors may be able to declare a fire source and also declare a non possibility if both of the heat sensors are returning a lower value of the signal. This situation is particularly important where a choice of more realistic sensors was made. This combination has seven declaration modes that span on a variety of combinations and individual sensor readings. That in itself is a deterrent against sensor malfunction.

The detection modes in this case would be illustrated by an equation different from eq. 7.1, as follows

$$A_1 \text{ or } B_1 \text{ or } A_2B_3 \text{ or } A_3B_2 \text{ or } A_2C_3 \text{ or } B_2C_3 \text{ or } A_2B_2C_1 \quad (7.7)$$

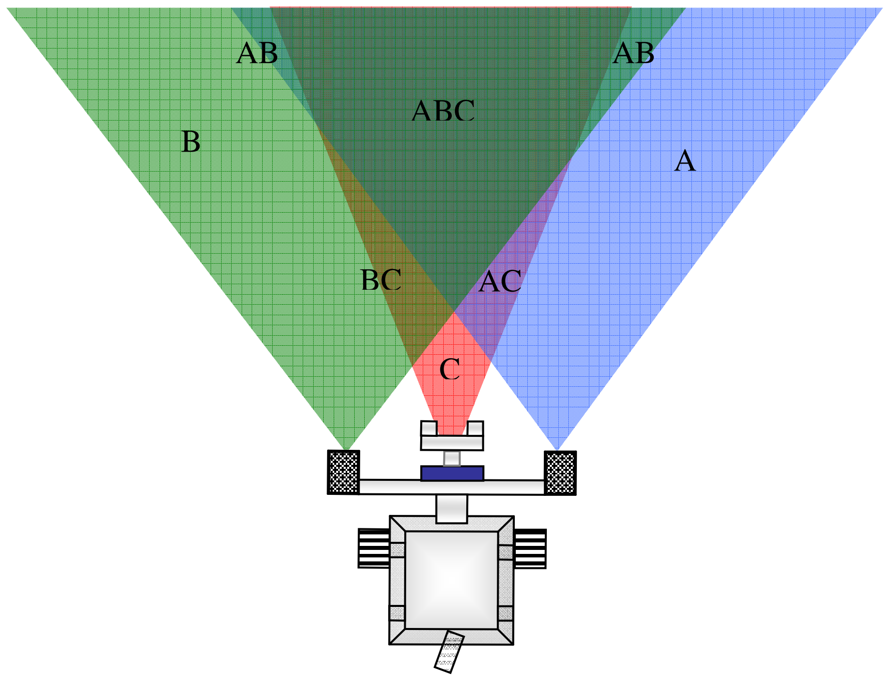


Figure 7. 7 Possible combinations of sensors with A and B as heat sensors and C as a light sensor

7.3.1 Derivation of Two-sensor detection modes

As previously described that the detection modes in this particular case would be
A_1 or B_1 or A_2B_3 or A_3B_2 or A_2C_3 or B_2C_3 or $A_2B_2C_1$

The chosen nomenclature in this case again is that the subscript 1 with the sensor is the declaration level confidence level and the subscript 4, as introduced in the modified voting logic, is the non-declaration level confidence level, which means that no possible combination with the highest values of the sensor C may contribute to the declaration of a source of fire.

It involves some lengthy calculations to derive the Boolean expression for these sensor combinations. In fact because of the seven available variable combinations, there are 120 terms that are generated. In order to get all possible combinations

$$\binom{n}{k} = \frac{P_{k,n}}{k!} = \frac{n!}{k!(n-k)!} \tag{7.8}$$

Where

$$P_{k,n} = \frac{n!}{(n-k)!} \tag{7.9}$$

All possible combinations for variables ABCDEFG would be as follows

One variable (7 Combinations):

A B C D E F

Two variables (21 Combinations):

AB AC AD AE AF AG BC BD BE BF BG CD
CE CF CG DE DF EF EG FG

Three variables (35 Combinations):

ABC ABD ABE ABF ABG ACD ACE ACF ACG AFG ADE ADF
ADG AEF AEG BCD BCE BCF BCG BDE BDF BDG BEF BFG
CDE CDF CDG CEF CEG CFG DEF DEG DFG EFG

Four Variables (35 Combinations):

ABCD	ABCE	ABCF	ABCG	ABDE	ABDF
ABDG	ABEF	ABEG	ACDE	ACDF	ACDG
ACEF	ACEG	ACFG	ADEF	ADEG	AEFG
ADFG	ABFG	BCDE	BCDF	BCDG	BCEF
BCEG	BCFG	BDEF	BDEG	BEFG	BDFG
CDEF	CDEG	CEFG	CDFG	DEFG	

Five variables (21 Combinations):

ABCDE	ABCDF	ABCDG	ABCEF	ABCEG	ABCFG
ABDEF	ABDEG	ABDFG	ABEFG	ACDEF	ACDEG
ACDFG	ACEFG	ADEFG	BCDEF	BCDEG	BCDFG
BDEFG	BCEFG	CDEFG			

Six variables (7 Combinations):

ABCDEF	ABCDEG	ACDEFG	ABCEFG	ABDEFG	ABCDFG
BCDEFG					

Seven Variables (1 Combination):

ABCDEFG

The system probability of detection has seven detection modes as follows:

$$System\ P_d = A_1\ or\ B_1\ or\ A_2B_3\ or\ A_3B_2\ or\ A_2C_3\ or\ B_2C_3\ or\ A_2B_2C_1 \quad (7.10)$$

As earlier, this equation may be expanded by repeated application of the Boolean algebra expression given as

$$P\{X \text{ OR } Y\} = P\{X\} + P\{Y\} - P\{XY\} \quad (6.2)$$

Hence the *System* P_d would be the addition of the one-variable terms, then subtraction of the two-variable terms, then addition of the three-variable terms, subtraction of the four-variable terms, addition of five-variable terms, subtraction of the six-variable terms and finally addition of the seven-variable term., while in the above mentioned combinations it may be considered as

A = A_1

B = B_1

C = A_2B_3

D = A_3B_2

E = A_2C3

F = B_2C3

And

G = $A_2B_2C_1$

The declaration modes are color-coded for the readers to better understand the terms and where they came from.

The equation 7.10 then gets expanded as follows

$$\textbf{System } \mathrm{P}_d = \mathrm{P}_d\{A_1\} + \mathrm{P}_d\{B_1\} + \mathrm{P}_d\{A_2B_3\} + \mathrm{P}_d\{A_3B_2\} + \mathrm{P}_d\{A_2C_3\} + \mathrm{P}_d\{B_2C_3\} + \mathrm{P}_d\{A_2B_2C_1\}$$

$$- \mathrm{P}_d\{A_1\ B_1\} - \mathrm{P}_d\{A_1\ A_2B_3\} - \mathrm{P}_d\{A_1\ A_3B_2\} - \mathrm{P}_d\{A_1\ A_2C_3\} - \mathrm{Pd}\{A_1\ B_2C_3\} - \mathrm{P}_d\{A_1\ A_2B_2C_1\} - \mathrm{P}_d\{B_1\ A_2B_3\} - \mathrm{P}_d\{B_1\ A_3B_2\} - \mathrm{P}_d\{B_1\ A_2C_3\} - \mathrm{P}_d\{B_1\ B_2C_3\} - \mathrm{P}_d\{B_1\ A_2B_2C_1\} - \mathrm{P}_d\{A_2B_3\ A_3B_2\} - \mathrm{P}_d\{A_2B_3\ A_2C_3\} - \mathrm{P}_d\{A_2B_3\ B_2C_3\} - \mathrm{P}_d\{A_2B_3\ A_2B_2C_1\} - \mathrm{P}_d\{A_3B_2\ A_2C_3\} - \mathrm{P}_d\{A_3B_2\ B_2C_3\} - \mathrm{P}_d\{A_3B_2\ A_2B_2C_1\} - \mathrm{P}_d\{A_2C_3\ B_2C_3\} - \mathrm{P}_d\{A_2C_3\ A_2B_2C_1\} - \mathrm{P}_d\{B_2C_3\ A_2B_2C_1\}$$

$$+ \mathrm{P}_d\{A_1\ B_1\ A_2B_3\} + \mathrm{P}_d\{A_1\ B_1\ A_3B_2\} + \mathrm{P}_d\{A_1\ B_1\ A_2C_3\} + \mathrm{P}_d\{A_1\ B_1\ B_2C_3\} + \mathrm{P}_d\{A_1\ B_1\ A_2B_2C_1\} + \mathrm{P}_d\{A_1\ A_2B_3\ A_3B_2\} + \mathrm{P}_d\{A_1\ A_2B_3\ A_2C_3\} + \mathrm{P}_d\{A_1\ A_2B_3\ B_2C_3\} + \mathrm{P}_d\{A_1\ A_2B_3\ A_2B_2C_1\} + \mathrm{P}_d\{A_1\ B_2C_3\ A_2B_2C_1\} + \mathrm{P}_d\{A_1\ A_3B_2\ A_2C_3\} + \mathrm{P}_d\{A_1\ A_3B_2\ B_2C_3\} + \mathrm{P}_d\{A_1A_3B_2\ A_2B_2C_1\} + \mathrm{P}_d\{A_1A_2C_3\ B_2C_3\} + \mathrm{P}_d\{A_1\ A_2C_3\ A_2B_2C_1\} + \mathrm{P}_d\{B_1\ A_2B_3\ A_3B_2\} + \mathrm{P}_d\{B_1\ A_2B_3\ A_2C_3\} + \mathrm{P}_d\{B_1\ A_2B_3\ B_2C_3\} + \mathrm{P}_d\{B_1\ A_2B_3\ A_2B_2C_1\} + \mathrm{P}_d\{B_1\ A_3B_2\ A_2C_3\} + \mathrm{P}_d\{B_1\ A_3B_2\ B_2C_3\} + \mathrm{P}_d\{B_1\ A_3B_2\ A_2B_2C_1\} + \mathrm{P}_d\{B_1\ A_2C_3\ B_2C_3\} + \mathrm{P}_d\{B_1\ A_2C_3\ A_2B_2C_1\} + \mathrm{P}_d\{B_1\ B_2C_3\ A_2B_2C_1\} + \mathrm{P}_d\{A_2B_3\ A_3B_2\ A_2C_3\} + \mathrm{P}_d\{A_2B_3\ A_3B_2\ B_2C_3\} + \mathrm{P}_d\{A_2B_3\ A_3B_2\ A_2B_2C_1\} + \mathrm{P}_d\{A_2B_3\ A_2C_3\ B_2C_3\} + \mathrm{P}_d\{A_2B_3\ A_2C_3\ A_2B_2C_1\} + \mathrm{P}_d\{A_2B_3\ B_2C_3\ A_2B_2C_1\} + \mathrm{P}_d\{A_3B_2\ A_2C_3\ B_2C_3\} + \mathrm{P}_d\{A_3B_2\ A_2C_3\ A_2B_2C_1\} + \mathrm{P}_d\{A_3B_2\ B_2C_3\ A_2B_2C_1\} + \mathrm{P}_d\{A_2C_3\ B_2C_3\ A_2B_2C_1\}$$

$$- \mathrm{P}_d\{A_1\ B_1\ A_2B_3\ A_3B_2\} - \mathrm{P}_d\{A_1\ B_1\ A_2B_3\ A_2C_3\} - \mathrm{P}_d\{A_1\ B_1\ A_2B_3\ B_2C_3\} - \mathrm{P}_d\{A_1\ B_1\ A_2B_3\ A_2B_2C_1\} - \mathrm{P}_d\{A_1\ B_1\ A_3B_2\ A_2C_3\} - \mathrm{P}_d\{A_1\ B_1\ A_3B_2\ B_2C_3\} - \mathrm{P}_d\{A_1\ B_1\ A_3B_2\ A_2B_2C_1\} - \mathrm{P}_d\{A_1\ B_1\ A_2C_3\ B_2C_3\} - \mathrm{P}_d\{A_1\ B_1\ A_2C_3\ A_2B_2C_1\} - \mathrm{P}_d\{A_1\ A_2B_3\ A_3B_2\ A_2C_3\} - \mathrm{P}_d\{A_1\ A_2B_3\ A_3B_2\ B_2C_3\} - \mathrm{P}_d\{ \tag{7.11}$$

$A_1\ A_2B_3\ A_3B_2\ A_2B_2C_1\} - P_d\{A_1\ A_2B_3\ A_2C_3\ B_2C_3\} - P_d\{A_1\ A_2B_3\ A_2C_3$

$A_2B_2C_1\} - P_d\{A_1\ A_2B_3\ B_2C_3\ A_2B_2C_1\} - P_d\{A_1\ A_3B_2\ A_2C_3\ B_2C_3\} - P_d\{A_1$

$A_3B_2\ A_2C_3\ A_2B_2C_1\} - P_d\{A_1\ A_2C_3\ B_2C_3\ A_2B_2C_1\} - P_d\{A_1\ A_3B_2\ B_2C_3$

$A_2B_2C_1\} - P_d\{A_1\ B_1\ B_2C_3\ A_2B_2C_1\} - P_d\{B_1\ A_2B_3\ A_3B_2\ A_2C_3\} - P_d\{B_1$

$A_2B_3\ A_3B_2\ B_2C_3\} - P_d\{B_1\ A_2B_3\ A_3B_2\ A_2B_2C_1\} - P_d\{B_1\ A_2B_3\ A_2C_3\ B_2C_3\}$

$- P_d\{B_1\ A_2B_3\ A_2C_3\ A_2B_2C_1\} - P_d\{B_1\ A_2B_3\ B_2C_3\ A_2B_2C_1\} - P_d\{B_1\ A_3B_2$

$A_2C_3\ B_2C_3\} - P_d\{B_1\ A_3B_2\ A_2C_3\ A_2B_2C_1\} - P_d\{B_1\ A_2C_3\ B_2C_3\ A_2B_2C_1\} -$

$P_d\{B_1\ A_3B_2\ B_2C_3\ A_2B_2C_1\} - P_d\{A_2B_3\ A_3B_2\ A_2C_3\ B_2C_3\} - P_d\{A_2B_3\ A_3B_2$

$A_2C_3\ A_2B_2C_1\} - P_d\{A_2B_3\ A_2C_3\ B_2C_3\ A_2B_2C_1\} - P_d\{A_2B_3\ A_3B_2\ B_2C_3\ A_2B_2C_1\}$

$- P_d\{A_3B_2\ A_2C_3\ B_2C_3\ A_2B_2C_1\}$

$+ P_d\{A_1\ B_1\ A_2B_3\ A_3B_2\ A_2C_3\} + P_d\{A_1\ B_1\ A_2B_3\ A_3B_2\ B_2C_3\} + P_d\{A_1\ B_1$

$A_2B_3\ A_3B_2\ A_2B_2C_1\} + P_d\{A_1\ B_1\ A_2B_3\ A_2C_3\ B_2C_3\} + P_d\{A_1\ B_1\ A_2B_3\ A_2C_3$

$A_2B_2C_1\} + P_d\{A_1\ B_1\ A_2B_3\ B_2C_3\ A_2B_2C_1\} + P_d\{A_1\ B_1\ A_3B_2\ A_2C_3\ B_2C_3\} +$

$P_d\{A_1\ B_1\ A_3B_2\ A_2C_3\ A_2B_2C_1\} + P_d\{A_1\ B_1\ A_3B_2\ B_2C_3\ A_2B_2C_1\} + P_d\{A_1\ B_1$

$A_2C_3\ B_2C_3\ A_2B_2C_1\} + P_d\{A_1\ A_2B_3\ A_2C_3\ B_2C_3\ A_2B_2C_1\} + P_d\{A_1\ A_2B_3\ A_3B_2$

$A_2C_3\ B_2C_3\} + P_d\{A_1\ A_2B_3\ A_3B_2\ A_2C_3\ A_2B_2C_1\} + P_d\{A_1\ A_2B_3\ A_3B_2\ B_2C_3$

$A_2B_2C_1\} + P_d\{A_1\ A_3B_2\ A_2C_3\ B_2C_3\ A_2B_2C_1\} + P_d\{B_1\ A_2B_3\ A_3B_2\ A_2C_3\ B_2C_3\}$

$+ P_d\{B_1\ A_2B_3\ A_3B_2\ A_2C_3\ A_2B_2C_1\} + P_d\{B_1\ A_2B_3\ A_3B_2\ B_2C_3\ A_2B_2C_1\} + P_d\{$

$B_1\ A_3B_2\ A_2C_3\ B_2C_3\ A_2B_2C_1\} + P_d\{B_1\ A_2B_3\ A_2C_3\ B_2C_3\ A_2B_2C_1\} + P_d\{A_2B_3$

$A_3B_2\ A_2C_3\ B_2C_3\ A_2B_2C_1\}$

$- P_d\{A_1\ B_1\ A_2B_3\ A_3B_2\ A_2C_3\ B_2C_3\} - P_d\{A_1\ B_1\ A_2B_3\ A_3B_2\ A_2C_3\ A_2B_2C_1\}$

$- P_d\{A_1\ A_2B_3\ A_3B_2\ A_2C_3\ B_2C_3\ A_2B_2C_1\} - P_d\{A_1\ B_1\ A_2B_3\ A_2C_3\ B_2C_3$

$A_2B_2C_1\} - P_d\{A_1\ B_1\ A_3B_2\ A_2C_3\ B_2C_3\ A_2B_2C_1\} - P_d\{A_1\ B_1\ A_2B_3\ A_3B_2\ B_2C_3$

$A_2B_2C_1\}$ – P_d { B_1 A_2B_3 A_3B_2 A_2C_3 B_2C_3 $A_2B_2C_1$} + P_d { A_1 B_1 A_2B_3 A_3B_2 A_2C_3 B_2C_3 $A_2B_2C_1$}	

The confidence levels of each sensor is independent of others because of these being non-nested sensors, hence the expression for union and intersection that are applicable are as follows:

$$P_d\{A_1 \cup A_2\} = P_d\{A_1\} + P_d\{A_2\} \qquad (6.4)$$

$$P_d\{A_1 \cap A_2\} = 0 \qquad (6.5)$$

Hence the simplified system detection probability expression becomes:

$$\textbf{System } \mathbf{P}_{\boldsymbol{d}} = P_d\{A_1\}+P_d\{B_1\}+P_d\{A_2B_3\}+P_d\{A_3B_2\}+P_d\{A_2C_3\}$$
$$+P_d\{B_2C_3\}+P_d\{A_2B_2C_1\}-P_d\{A_1 B_1\}- P_d\{A_1 B_2C_3\}- \qquad (7.12)$$
$$P_d\{B_1 A_2C_3\}$$

Applying the union expression given as:

$$P_d\{A_1 \cup A_2\} = P_d\{A_1\} + P_d\{A_2\} \qquad (6.4)$$

Yields:

$$\textbf{System } \mathbf{P}_{\boldsymbol{d}} = P_d\{A_1\}+P_d\{B_1\} + P_d\{A_2\}P_d\{B_3\} + P_d\{A_3\}P_d\{B_2\}$$
$$+P_d\{A_2\}P_d\{C_3\} + P_d\{B_2\}P_d\{C_3\} + P_d\{A_2\}P_d\{B_2\}P_d\{C_1\}- \qquad (7.13)$$

$P_d\{A_1\}P_d\{B_1\} - P_d\{A_1\}P_d\{B_2\}P_d\{C_3\} - P_d\{B_1\}P_d\{A_2\}P_d\{C_3\}$

Equation 7.13 can be used to determine the total system probability of detection.

Similarly the false-alarm probability of the current system would be as follows:

$$\textbf{System } \mathbf{P_{fa}} = P_{fa}\{A_1\} + P_{fa}\{B_1\} + P_{fa}\{A_2\} P_{fa}\{B_3\} + P_{fa}\{A_3\} P_{fa}\{B_2\} + P_{fa}\{A_2\} P_{fa}\{C_3\} + P_{fa}\{B_2\} P_{fa}\{C_3\} + P_{fa}\{A_2\} P_{fa}\{B_2\} P_{fa}\{C_1\} - P_{fa}\{A_1\} P_{fa}\{B_1\} - P_{fa}\{A_1\} P_{fa}\{B_2\} P_{fa}\{C_3\} - P_{fa}\{B_1\} P_{fa}\{A_2\} P_{fa}\{C_3\} \quad (7.14)$$

<u>The numerical values in tables 7.5-7.9 are assumed typical values just for illustrating the approach</u>.

Sensor Confidence Level	Sensor A				Sensor B			Sensor C		
	A_1	A_2	A_3	A_4	B_1	B_2	B_3	C_1	C_2	C_3
Detection distribution	350	550	800	1000	350	550	800	400	600	1000
Conditional probability	0.35	0.55	0.8	1.0	0.35	0.55	0.8	0.4	0.6	1.0

Table 7. 5 Conditional probabilities for sensors A, B and C in the current combination of the sensors

Sensor Confidence Level	Sensor A				Sensor B			Sensor C		
	A_1	A_2	A_3	A_4	B_1	B_2	B_3	C_1	C_2	C_3
Inherent Detection Probability	0.9	0.84	0.8	0.74	0.88	0.81	0.73	0.88	0.81	0.73

Table 7. 6 Inherent detection probabilities of the sensors A, B and C obtained as a result of distribution of detections

Substituting the values in the equation computed for the system detection probability (Equation No. 7.13)

$$\textbf{System } \mathbf{P_d} = P_d\{A_1\}+P_d\{B_1\} + P_d\{A_2\}P_d\{B_3\} + P_d\{A_3\}P_d\{B_2\}$$
$$+P_d\{A_2\}P_d\{C_3\} + P_d\{B_2\}P_d\{C_3\} + P_d\{A_2\}P_d\{B_2\}P_d\{C_1\} - \quad (7.13)$$
$$P_d\{A_1\}P_d\{B_1\} - P_d\{A_1\}P_d\{B_2\}P_d\{C_3\} - P_d\{B_1\}P_d\{A_2\}P_d\{C_3\}$$

System P_d = 0.315 + 0.315 + 0.29 + 0.33 + 0.07 – 0.11 – 0.11 – 0.11

System P_d = 0.99

Hence with the suggested sensor combination the detection probability of the system is 99%, which is above the current detection probabilities available for the sensor combinations.

This suggests a very accurate system in declaration of fires.

The next step is to calculate the system false alarm probability. For this purpose, equation 7.14 has been derived above.

$$\textbf{System P}_{\boldsymbol{fa}} = P_{fa}\{A_1\} + P_{fa}\{B_1\} + P_{fa}\{A_2\}\, P_{fa}\{B_3\} + P_{fa}\{A_3\}\, P_{fa}\{B_2\} + P_{fa}\{A_2\}\, P_{fa}\{C_3\} + P_{fa}\{B_2\}\, P_{fa}\{C_3\} + P_{fa}\{A_2\}\, P_{fa}\{B_2\}\, P_{fa}\{C_1\} - P_{fa}\{A_1\}\, P_{fa}\{B_1\} - P_{fa}\{A_1\}\, P_{fa}\{B_2\}\, P_{fa}\{C_3\} - P_{fa}\{B_1\}\, P_{fa}\{A_2\}\, P_{fa}\{C_3\} \quad (7.14)$$

The typical false alarm probabilities may be obtained from the following tables as provided by the sensor manufacturers. Note that in this combination, sensor A and sensor B have the same values as they describe the heat (Thermal Infrared sensors) by Dexter industries. Both of these sensors are capable of the single sensor detection but the single sensor non possibility does not apply in this situation, as both of these sensors have to return values below certain levels for the non-possibility modes.

Sensor Confidence Level	Sensor A			
	A_1	A_2	A_3	A_4
Inherent false alarm Probability	1.06×10^{-4}	1.8×10^{-3}	1.4×10^{-3}	1.01×10^{-2}

Table 7. 7 Inherent false alarm probabilities for sensor A at different confidence

Sensor Confidence Level	Sensor B			
	B_1	B_2	B_3	B_4
Inherent false alarm Probability	1.06×10^{-4}	1.8×10^{-3}	1.4×10^{-3}	1.01×10^{-2}

levels

Table 7. 8 *Inherent false alarm probabilities for sensor B at different confidence levels*

Sensor Confidence Level	Sensor B		
	C_1	C_2	C_3
Inherent false alarm Probability	3.5×10^{-4}	2.0×10^{-3}	1.0×10^{-3}

Table 7. 9 Inherent false alarm probabilities for sensor C at different confidence levels

System P_{fa} = $3.7\times10^{-5} + 3.7\times10^{-5} + 1.1\times10^{-6} + 9.9\times10^{-7} + 1.37\times10^{-10} - 1.37\times10^{-9} - 3.66\times10^{-11} - 3.66\times10^{-11}$

Hence the false alarm probability of the system becomes:

System P_{fa} = 7.6×10^{-5}

Chapter 8
LabVIEW Program

The LabVIEW program written for the thesis consists of four parts

1. Sinusoidal (or zig-zag) movement
2. Obstacle avoidance
3. Fire detection and approach
4. Fire declaration

Sinusoidal movement part of the program is only in effect until higher level of any of the variables of interest such as intense light or temperature above a certain threshold are detected.

Obstacle avoidance is a continuous process that only comes into play when an obstacle is detected that is closer to the robot than the allowable distance predefined by the programmer. In this case the distance is 25 cm.

Fire detection is also a continuous process that follows the light or the heat as the robot detects the fire source. It is important to know that this fire detection process does not have a role in the decision making process of declaration of fire. This is strictly to find the highest possible gradient until it reaches the desired predefined values and at that point the navigation stops.

Fire declaration is the core of this research. It allows the user to see how the sensor confidence levels play a part in declaration of a fire source. LabVIEW allows the reader to see graphically how these sensor arrangements are made and it is self explanatory. The screenshots of the program will have labels to describe the process

8.1 Sinusoidal or Zigzag Movement

Figures 8.1 and 8.2 show the open-loop movement control of the robot before the values of light and temperature acquired by all three sensors are below the value of 60 lumens and 60°C. . When the case structure is on an even point the values given to the motors correspond to label A and when it is at odd numbers, which is every second, the information given to the motors is represented in label H in figure 8.2 Label B are the connecting circuits giving commands to the motors as when to run and when to stop or slow down. Label C is the time delay carefully chosen to control the amplitude of the curve the robot is assuming. Labels D and E represent the values of light and heat combined in a three input OR gate whereas label F defines the condition of these values to be above 60 lumens or centigrade. Label G is the stopping condition, as the values returned by any sensors fulfil the requirement of being above 60, the while loop stops.

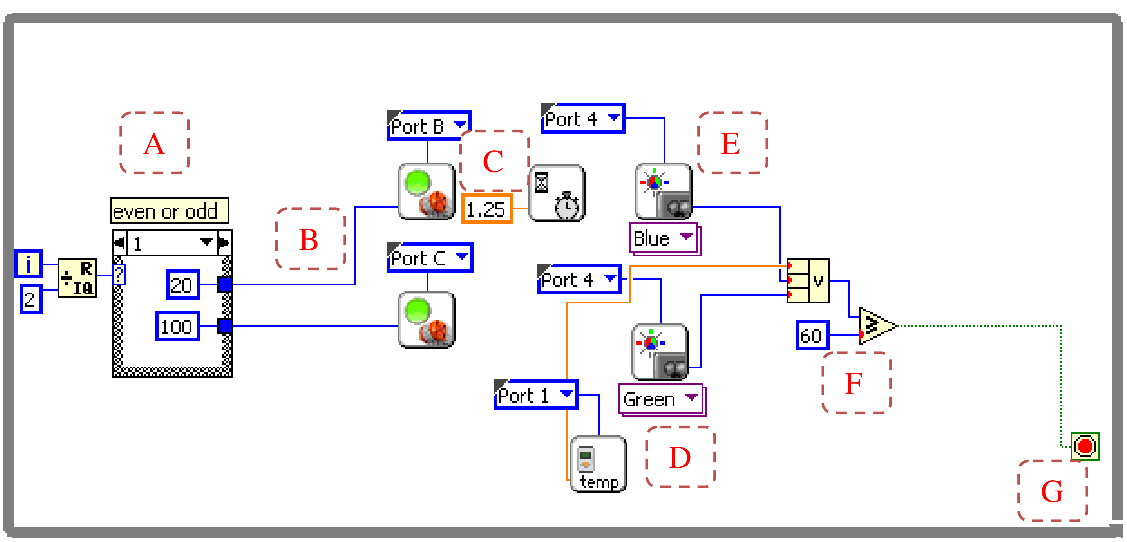


Figure 8. 1 Movement control of the robot before elevated heat or light has been detected

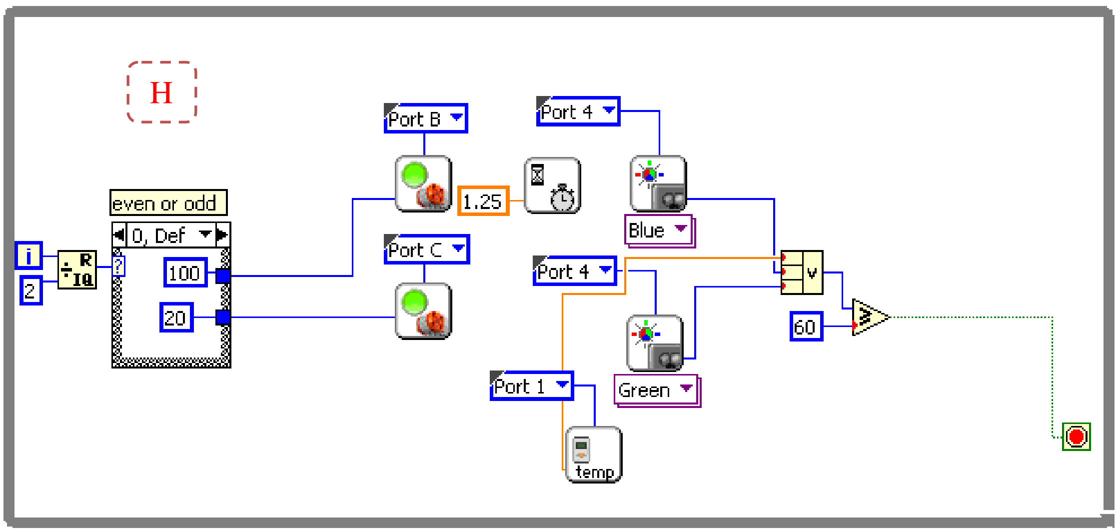


Figure 8. 2 Case structure showing even values at label "H"

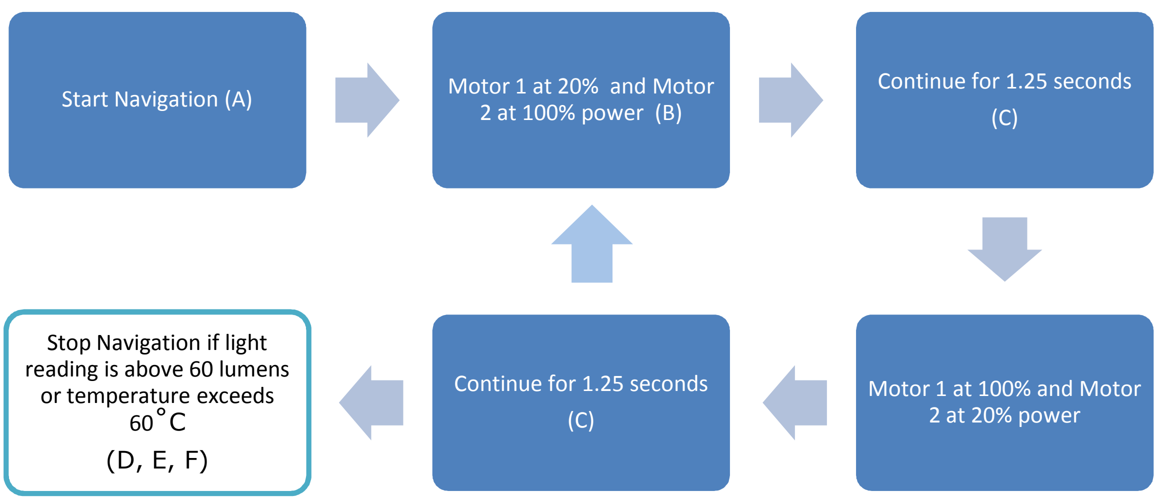


Figure 8. 3 Block diagram for zigzag movement

Figures 8.1 and 8.2 show the open-loop movement control of the robot before the values of light and temperature acquired by all three sensors are below the value of 60 lumens and 60°C. . When the case structure is on an even point the values given to the motors correspond to label A and when it is at odd numbers, which is every second, the information given to the motors is represented in label H in figure 8.2 Label B are the connecting circuits giving commands to the motors as when to run and when to stop or slow down. Label C is the time delay carefully chosen to control the amplitude of the curve the robot is assuming. Labels D and E represent the values of light and heat combined in a three input OR gate whereas label F defines the condition of these values to be above 60 lumens or centigrade. Label G is the stopping condition, as the values returned by any sensors fulfil the requirement of being above 60, the while loop stops.

8.2 Obstacle Avoidance

One of the integral parts of the robot navigation is obstacle avoidance. As evident by the name it will ensure that the robot does not run into other objects, walls and humans. For this purpose a SONAR sensor was used. This ultrasonic sensor has been described in detail in Chapter 3 under section 3.22.

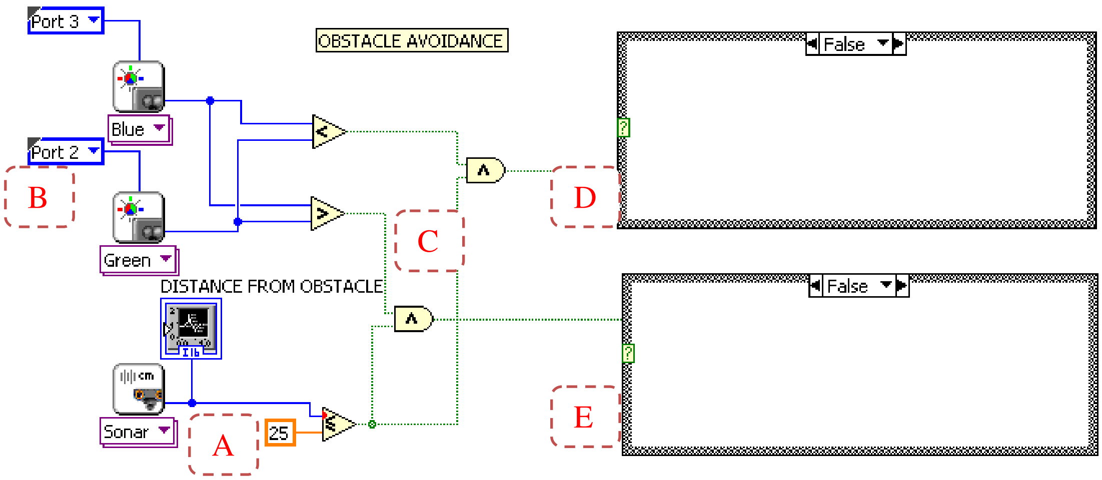


Figure 8. 4   No actions taken while the obstacle is more than 25 cm away

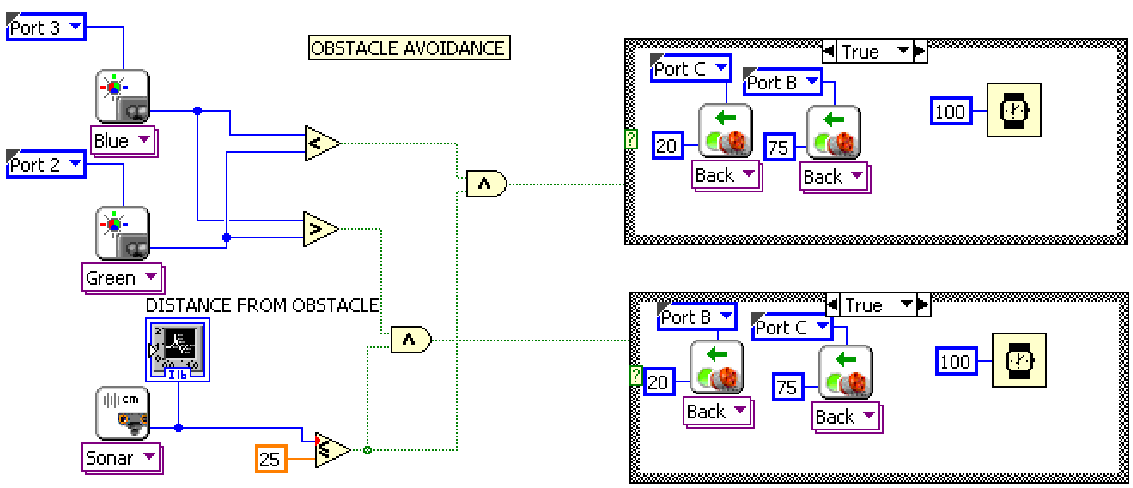


Figure 8. 5   Obstacle Avoidance with light intensity comparison

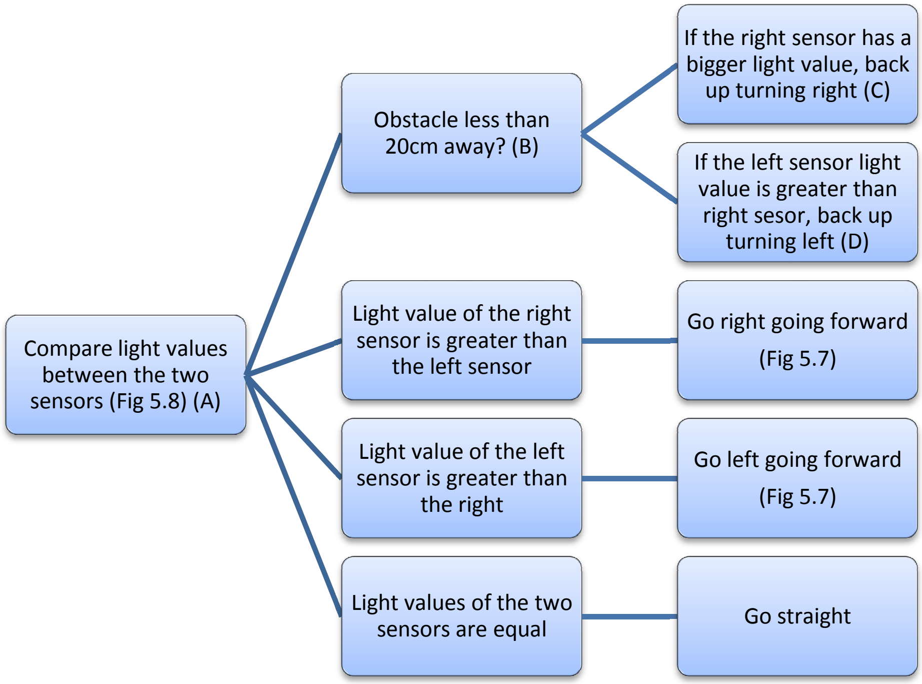


Figure 8. 6 Block diagram for smart obstacle avoidance

Simple obstacle avoidance would consist of a sonar reading to be less then a predefined value in centimeters or inches for the robot to change its trajectory. In this case there was another consideration taken into account as to which direction the robot would turn provided an obstacle is detected closer than the allowable distance from the robot. For this, the two light sensors were also taken into account.

If the distance of the robot from the obstacle is more than 25 cm, it does not come into effect. (Fig 8.4). But as in Figure 8.5, when an obstacle is detected (Label A) the two light sensors are consulted (Label B) and the direction of backing up depends upon the values provided by the sensors. If the right sensor exhibits higher light value, the robot will back up facing right(Label D), and if the left light sensor is having a higher light intensity value than the right sensor, it would back up facing to the left (Label E).

This addition to the obstacle avoidance greatly increases the efficiency of the system as the robot not only becomes less likely to get stuck but also it reduces the navigation time of the robot considerably to reach the goal.

In other cases the obstacle avoidance may also just be defined as backing up straight for a set distance from an obstacle.

8.3 Fire Detection and Approach

Part of the program written for the fire detection and approach follows a simple comparison between the two light sensors. First of all, it needs to be kept in mind that the robot is already moving at this point in a zigzag pattern motion. As soon as one of sensors detects an elevated value of light or heat, this part of the program comes into effect, ending the zigzag motion pattern and starting the light following algorithm.

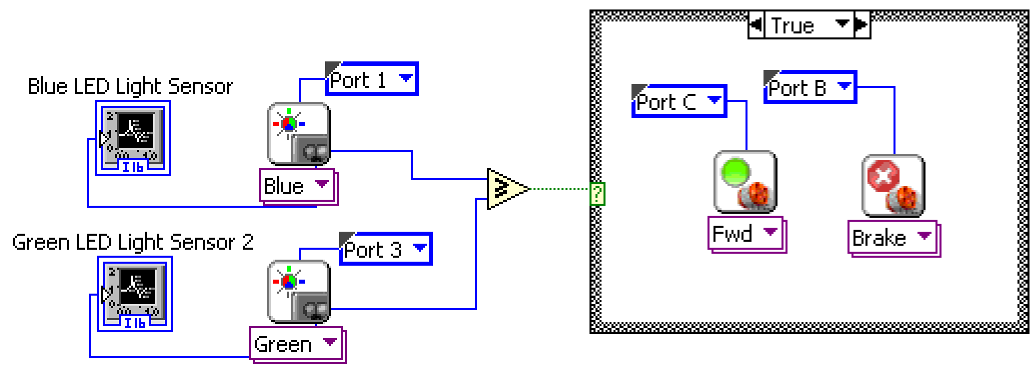


Figure 8. 7 Light following program while light sensor connected to Port 1 has a higher value than the one connected to Port 2 (Robot turns right)

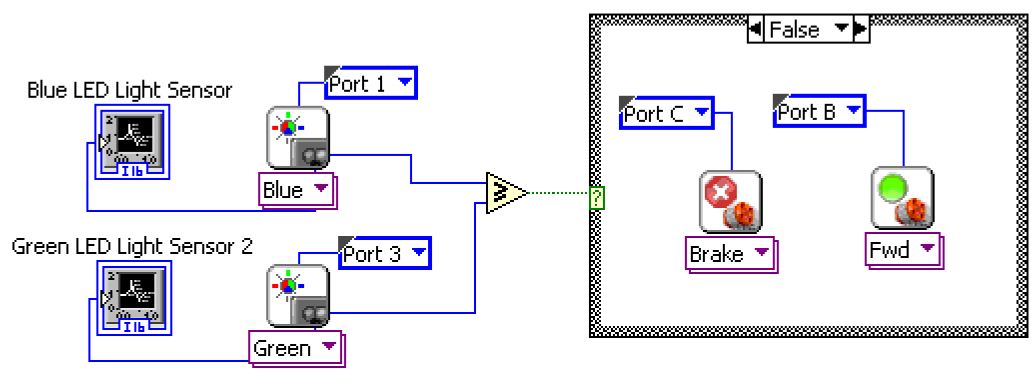


Figure 8. 8 Light trail following while light sensor connected to Port 2 has a higher value than the one connected to port 1 (Robot turns left)

8.4 Fire Declaration

After the robot has followed the trail of light and heat and is getting closer to the fire source, there has to be a mechanism to declare whether the approached source is fire or not. In Chapter 6 and Chapter 7 this is described in detail because certain variables come into play in this regard and finding the correct combination of the sensor readings to declare a fire has to be deployed.

8.4.1 Confidence Level Definitions

The first part is to define what value has to return which confidence level, for example in the case of two light sensors and one thermal infrared sensor, the thermal infrared sensor is named sensor A. Numerical values are assumed plausible values to illustrate how the approach works. If the value of A is below 60°C, there is no possibility of fire. This value can be considered as A1, which is the fire non-possibility mode. In Chapter 7 it was defined that at level A1, the fire is not possible no matter what values other sensors may provide. Also a temperature value between 60°C and 100°C is considered to be the medium confidence level, denoted by A2. Meanwhile, the temperature values between 100°C and 115°C are considered to be high confidence. Declaration of fire may happen at these values depending upon the readings from other sensors, as that may be considered supporting evidence for the presence of fire. Finally if the temperature reading returned by the sensor A is above 115°C, a fire has to be present there. That level of confidence is denoted as A4, and this is also called Single Sensor Declaration Mode. According to the derivations in Chapter 7, this would be considered the declaration of fire.

An illustration of confidence levels is given in the following figure, as they were defined in LabVIEW.

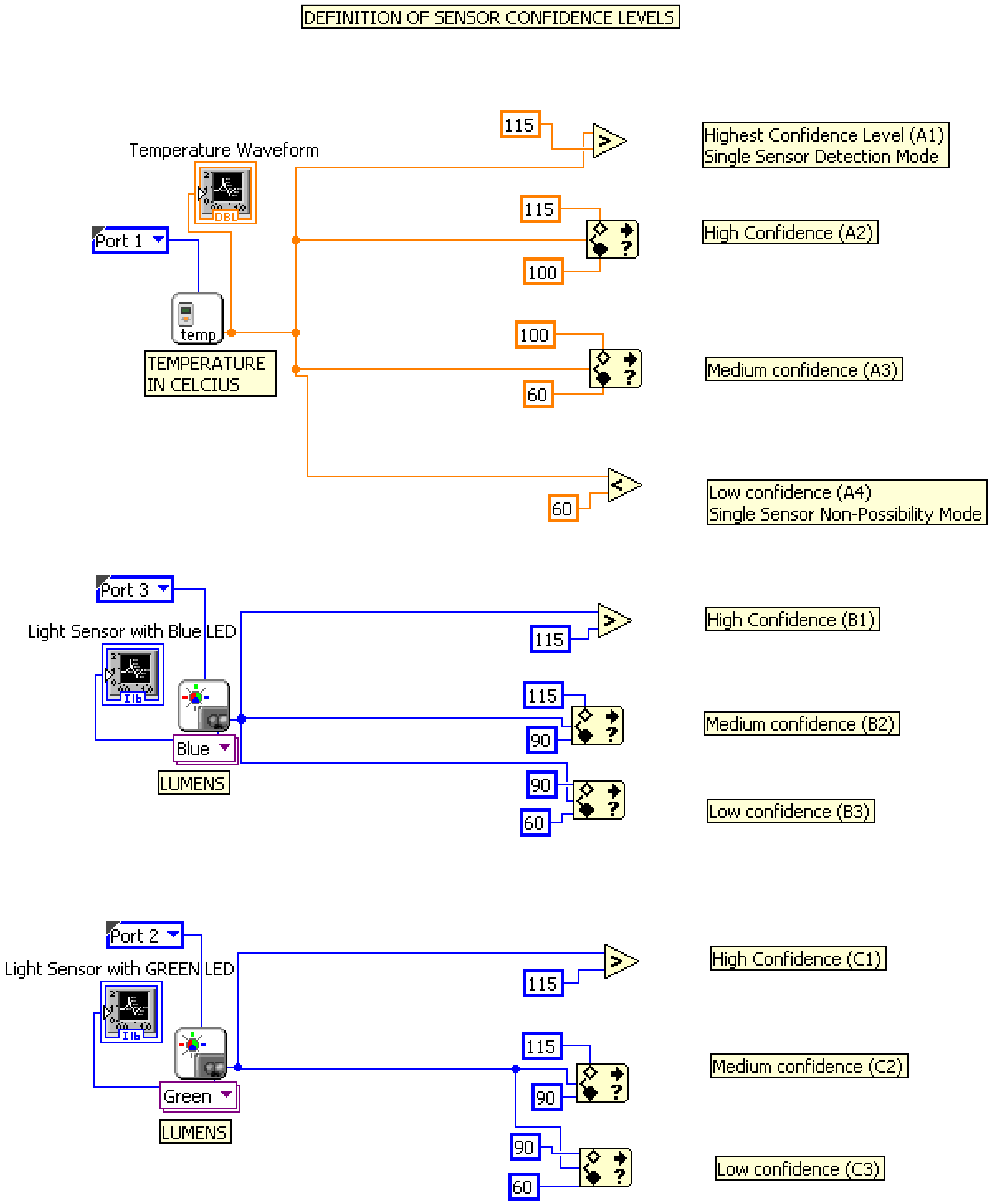


Figure 8. 9 Sensors and confidence levels

Figure 8.9 describes the different confidence levels as defined by the programmer. For the TIR (Thermal Infrared Sensor), four confidence levels have been defined namely temperature below 60° C, which is confidence level A4. This is the single sensor non-possibility value as it is impossible to have a fire incident no matter what values are returned by the light sensors. When the temperature value returned by the sensor is between 60°C and 100°C, a medium confidence level is declared. A high confidence value is declared between 100°C and 115°C. Medium and high confidence values are even though not a detection mode but the possibility of fire being present there would depend upon the "vote" and confidence levels from the other sensors in the process of identifying a fire. The confidence level A1 is declared when temperature readings returned by the sensor are above 115°C. At this point the software identifies the reading as a positive identification of fire, as these temperatures are not achieved by other objects normally.

Also the confidence levels of the two light sensors can be seen labelled as B1, B2 B3 and C1 C2 and C3. Defining the high, medium and low confidence levels respectively for the light sensors B and C.

Point to be noted is that the low confidence level starts at 60 Lumens. As described previously, below 60 Lumens, the robot goes through a sinusoidal or zigzag movement increasing its peripheral vision. When lights under 60 Lumens are detected it is not considered to be a trail guidance signal. Hence between the light values of 60 and 90 Lumens, a low confidence is defined. Between 90 and 115 Lumens a medium confidence level and above 115 Lumens, high confidence level is defined.

8.4.2 Detection Modes (Confidence Level Combinations)

As described previously a combination of confidence levels of different sensors that declares a particular incident is called a *Detection Mode.* The following two scenarios were programmed in LabVIEW for declaration of fire source

8.4.2.1 LabVIEW VI for Two Light Sensors and One TIR Sensor

In the case of two light sensors and one temperature sensor, the detection modes defined were described in Equation 7.1 as follows

$$\boldsymbol{A_1} \textit{ or } \boldsymbol{A_2B_2} \textit{ or } \boldsymbol{A_2C_2} \textit{ or } \boldsymbol{A_3B_1C_2} \textit{ or } \boldsymbol{A_3B_2C_1} \tag{7.1}$$

This means:

If the sensor A which is the temperature sensor detects heat at the confidence level A1 (Above 115°C) **OR** Sensor A has a confidence level A2 AND sensor B has the confidence level B2 **OR** Sensor A is at a confidence level A2 AND sensor C has the confidence level C2 **OR** Sensor A has a confidence level **A3** AND Sensor B has confidence level B1 AND sensor C has confidence level C2 **OR**

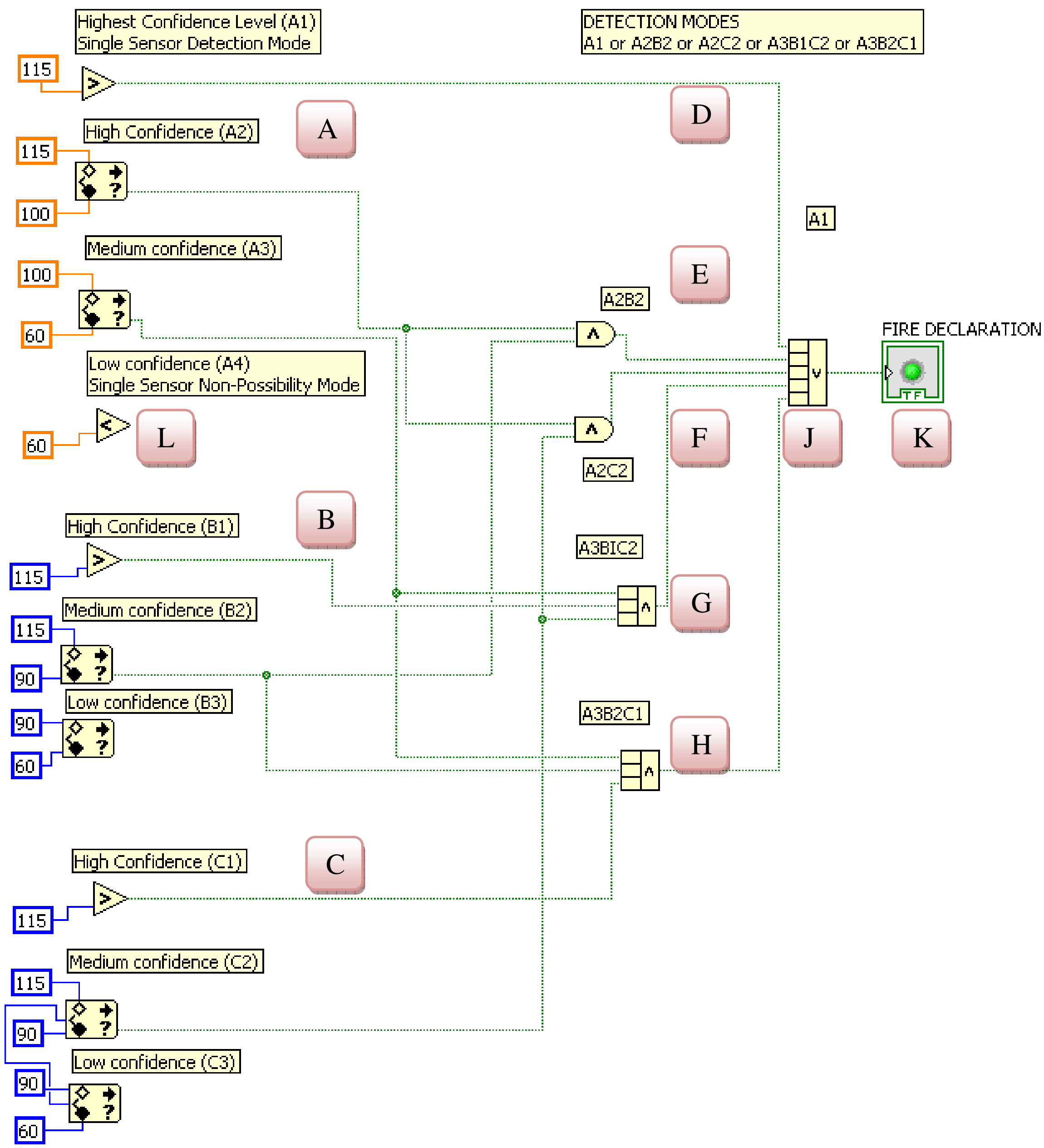


Figure 8. 10 Detection Modes in accordance to Eq. 7.1

Figure 8.10 describes the detection modes as defined in Equation 7.1. These combinations, when obtained from the robot sensors, will be able to define a condition that there is a fire present in a close vicinity of the robot.

8.4.2.2 LabVIEW VI for One Light Sensor and Two TIR Sensors

Similarly the VI (LabVIEW Virtual Instrument) for the case of two temperature sensors and one light sensor can be created.

The Detection Modes for that case are given by equation 7.7 i.e.

$$\boldsymbol{A_1} \text{ or } \boldsymbol{B_1} \text{ or } \boldsymbol{A_2 B_3} \text{ or } \boldsymbol{A_3 B_2} \text{ or } \boldsymbol{A_2 C_3} \text{ or } \boldsymbol{B_2 C_3} \text{ or } \boldsymbol{A_2 B_2 C_1} \qquad (7.7)$$

The sensor arrangement also needs to be changed. As previously described the single sensor non-possibility mode does not apply in this case as the two TIR sensors can declare fire individually. Hence the acceptable detection modes consist of seven parts.

The LabVIEW program will need to accommodate these seven detection modes. Figure 8.9 describes the confidence levels of this sensor arrangement and the confidence levels associated with each sensor for a particular sensor detected value.

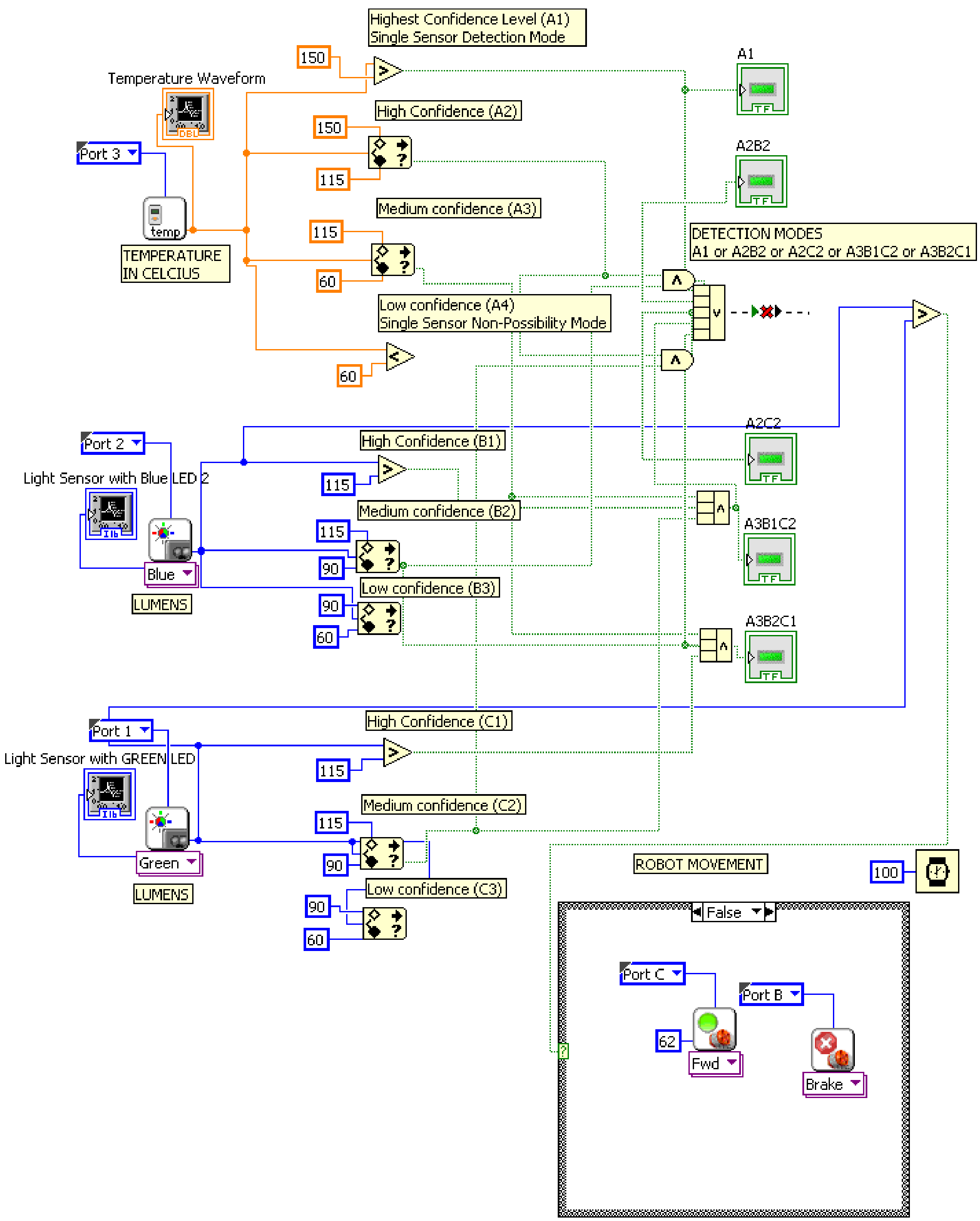


Figure 8. 11 The actual detection VI for this sensor arrangement

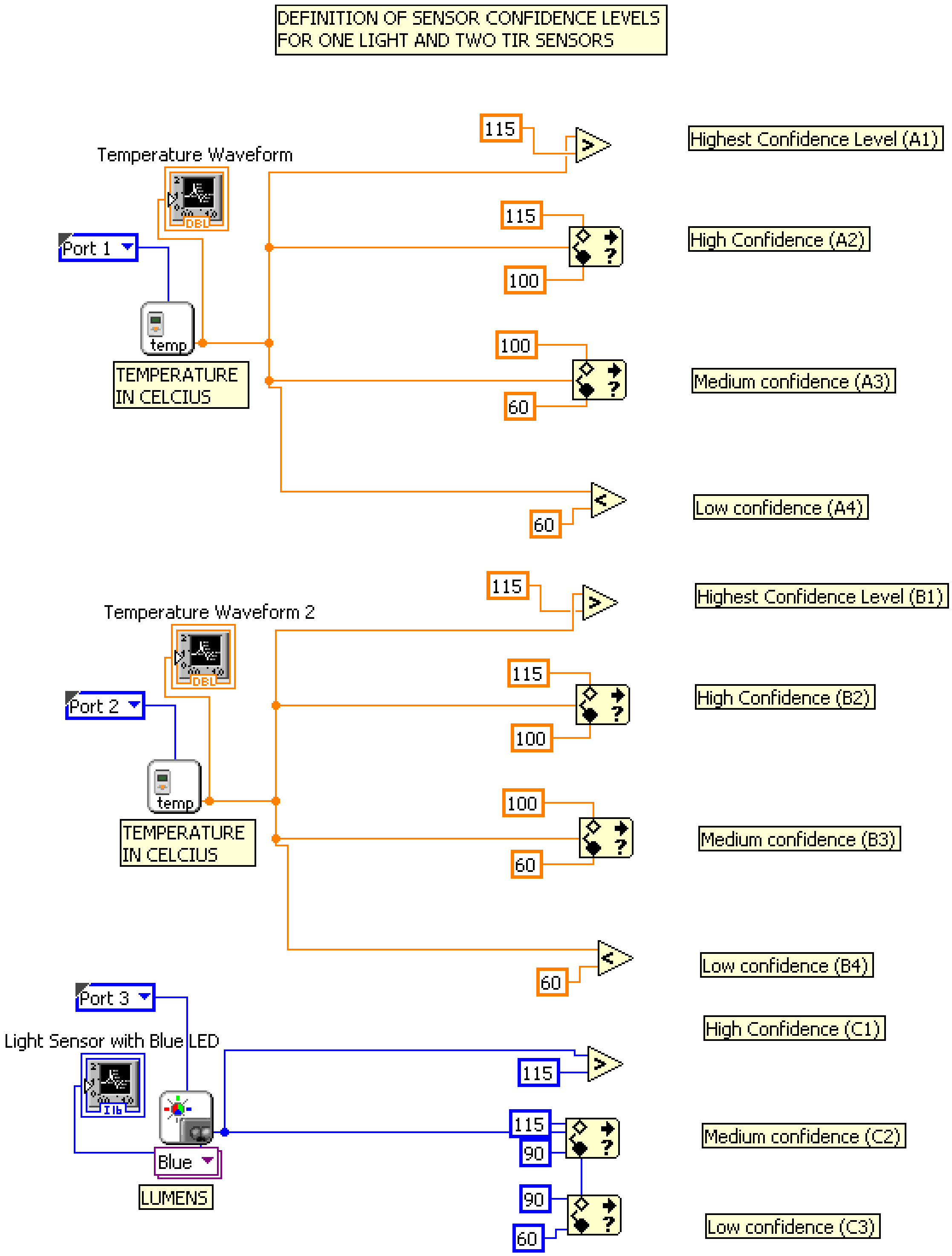


Figure 8. 12   Confidence level definition for the case of two TIR sensors and one light sensor

At this point detection modes may be applied to the VI.

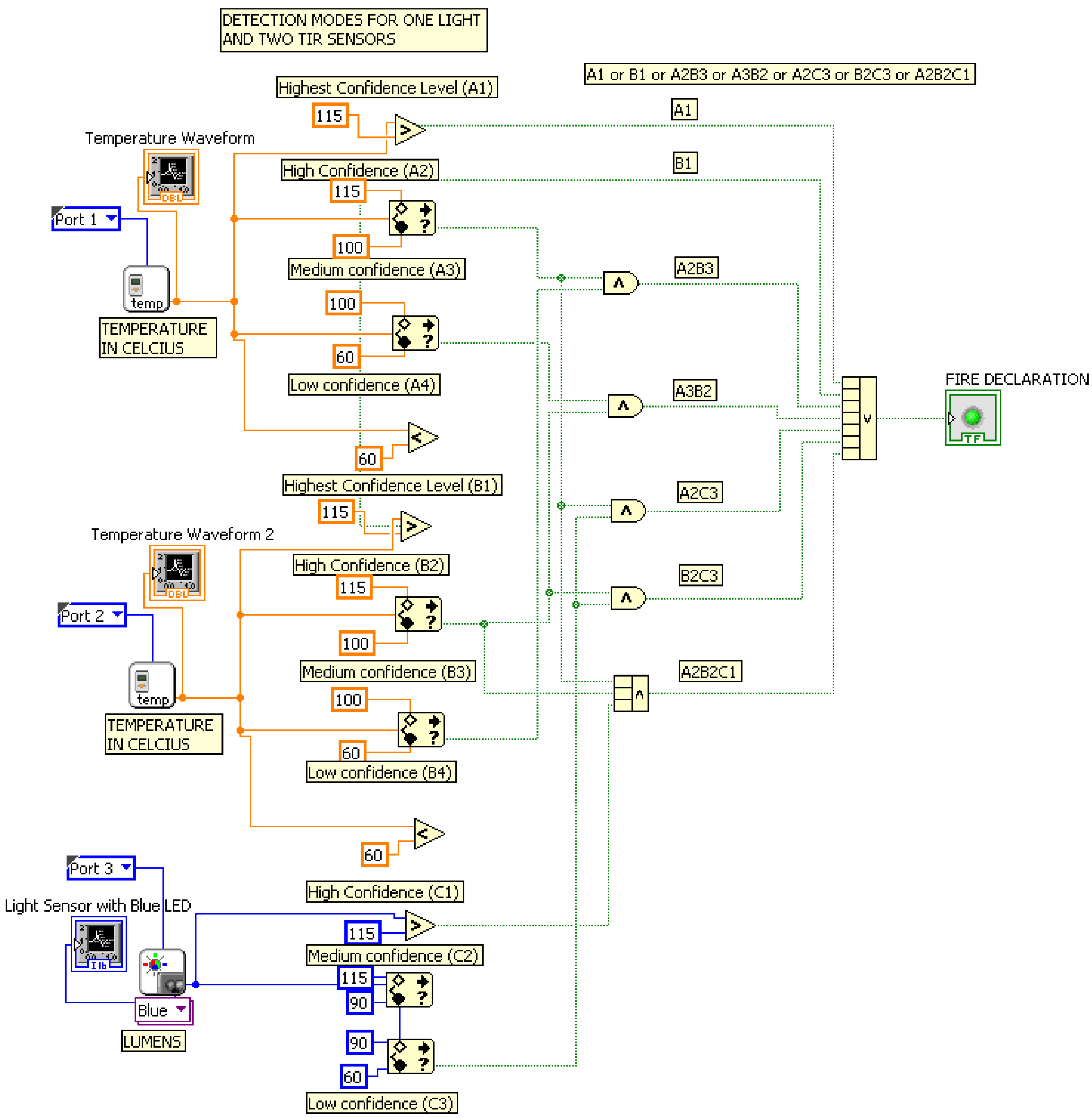


Figure 8. 13 Detection Modes for two TIR and one Light sensor arrangement in accordance to eq. 7.7

Fire Declaration is a Boolean switch activated by any one of the detection modes. This switch may start other operations such as fire extinguishing mechanism or an alarm. In this VI, Motor connected to port A (also called *Motor A*) is one of the outputs still available. To show the mechanism, the motor will run for one second declaring the fire.

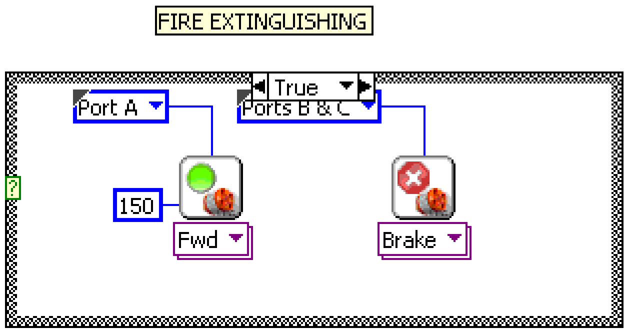


Figure 8. 14 Open loop control of Motor A is running indicating the true condition of the presence of fire

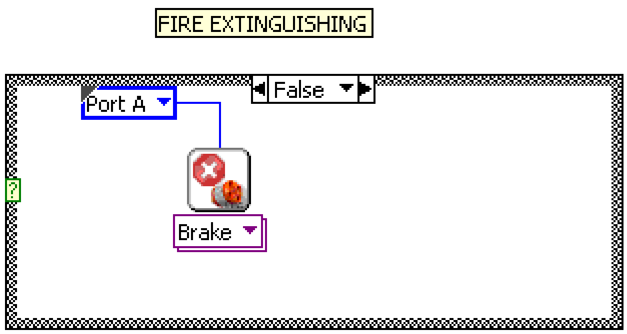
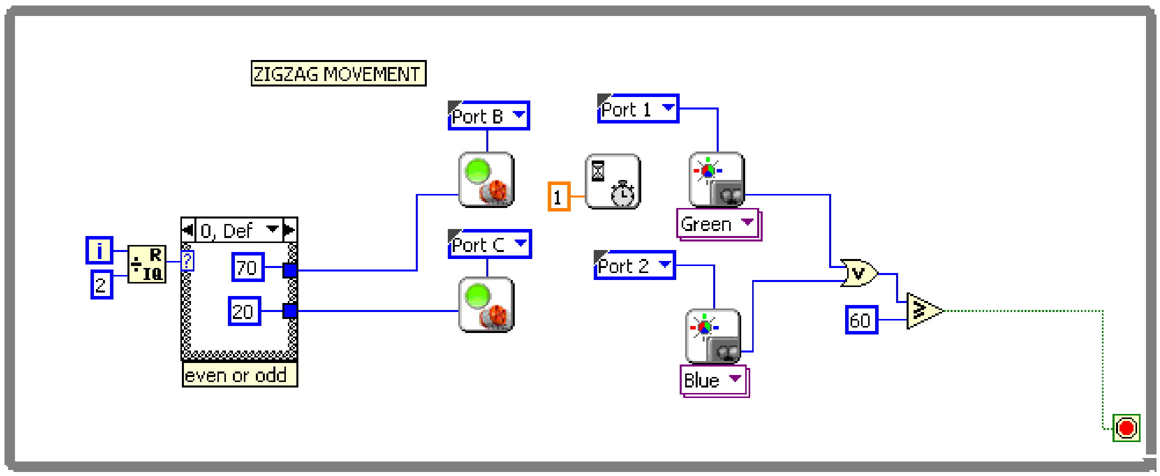


Figure 8. 15 Open loop control of Motor A is stopped indicating the false condition of the presence of fire

It is to be noted that in the true condition of the presence of fire, Motor B and Motor C, which are the driving motors are also stopped which prevents the robot to move away from the target.

The complete LabVIEW *Virtual Instrument* or VI is the combination of all the above mentioned conditions. The VI for the case of two light sensors and one TIR would become:



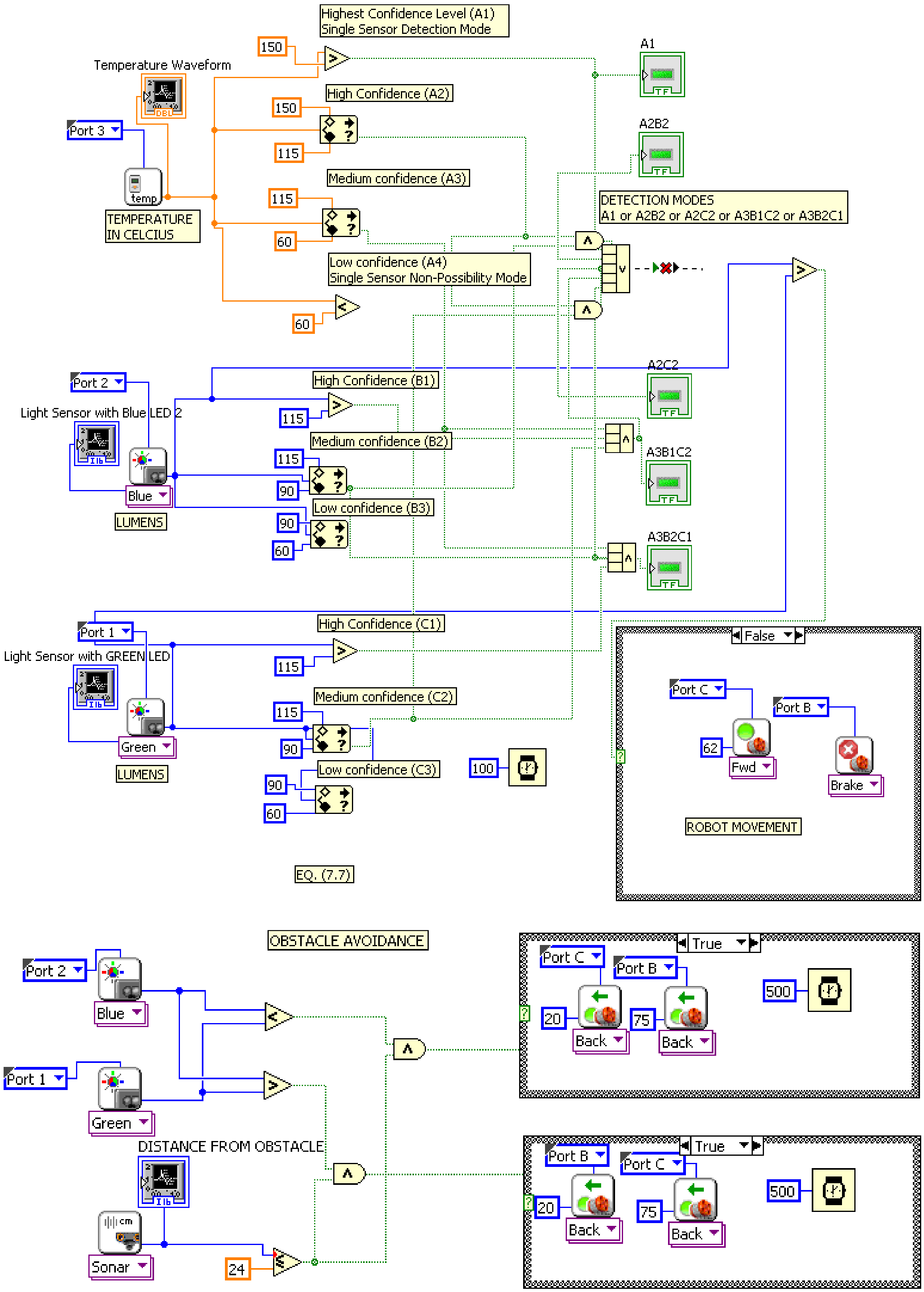

Highest Confidence Level (A1)
Single Sensor Detection Mode
150
Temperature Waveform
High Confidence (A2)
150
Port 3
115
Medium confidence (A3)
115
temp
TEMPERATURE
IN CELCIUS
60
Low confidence (A4)
Single Sensor Non-Possibility Mode
60
A1
A2B2
DETECTION MODES
A1 or A2B2 or A2C2 or A3B1C2 or A3B2C1
Port 2
Light Sensor with Blue LED 2
High Confidence (B1)
115
Medium confidence (B2)
115
90
Blue
LUMENS
Low confidence (B3)
90
60
A2C2
A3B1C2
A3B2C1
Port 1
Light Sensor with GREEN LED
High Confidence (C1)
115
Medium confidence (C2)
115
90
Green
LUMENS
Low confidence (C3)
90
60
100
False
Port C
Port B
62
Fwd
Brake
ROBOT MOVEMENT
EQ. (7.7)
OBSTACLE AVOIDANCE
Port 2
Blue
Port 1
Green
DISTANCE FROM OBSTACLE
cm
Sonar
24
True
Port C
Port B
20
Back
75
Back
500
True
Port B
Port C
20
Back
75
Back
500

Figure 8. 16 Complete LabVIEW VI for Fire Declaration algorithm with two light and one TIR sensors. Describing Eq. 7.4

Also the final program for the scenario with two TIR sensors and one light sensor would be as follows

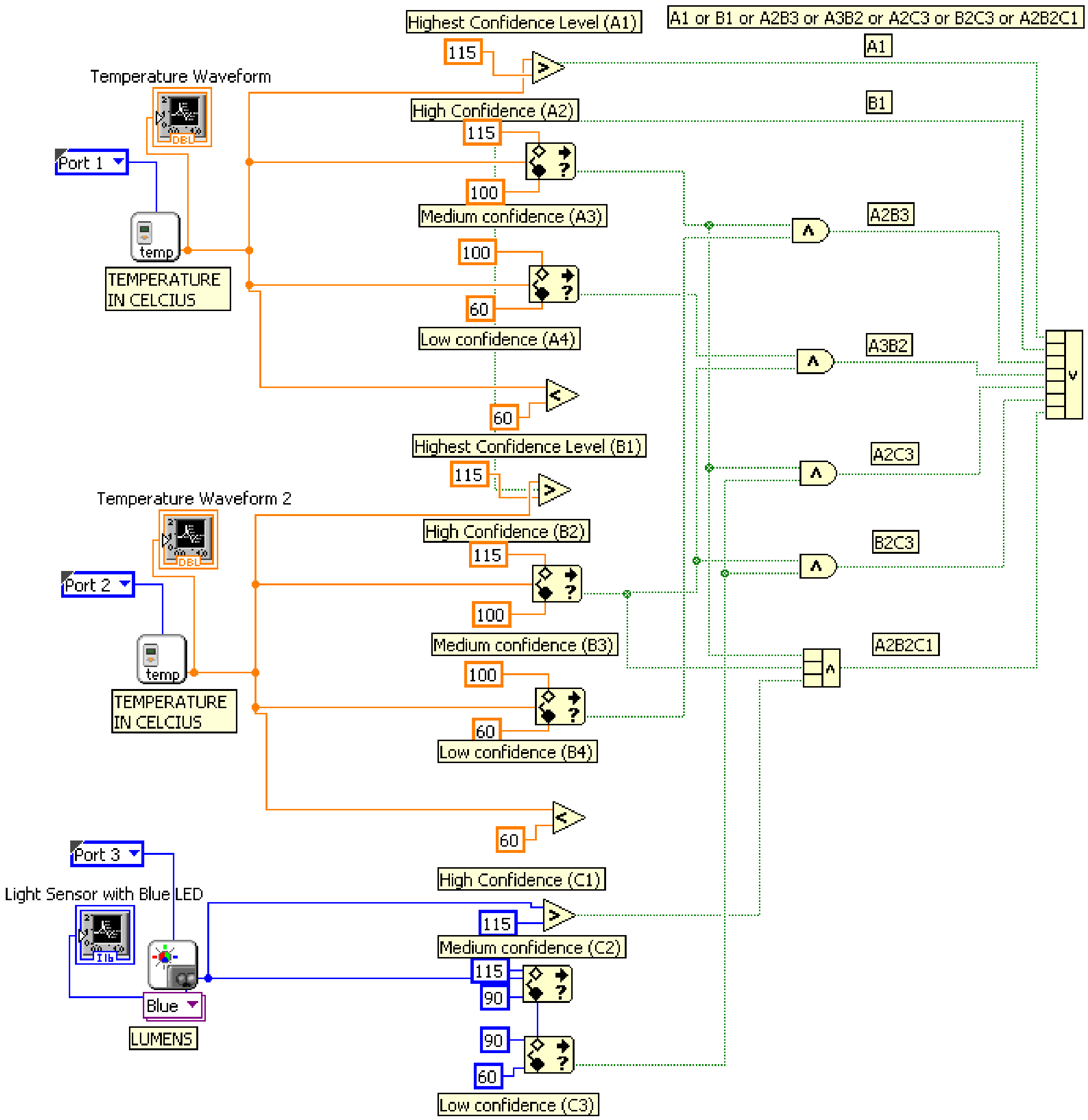


Figure 8. 17 Complete LabVIEW VI for Fire Declaration algorithm with one light and two TIR sensors in accordance with Eq. 7.7 (The other parts remain the same as figure 8.16

Chapter 9
Experimental Results

9.1 Introduction

Experiments were performed indicating different scenarios. As described in the previous chapters, two different sensor arrangements were used. In both the configurations, three sensors participated in decision making process of declaration of fire and one sensor was used for obstacle avoidance. Two different variations of algorithm were also applied to accommodate single sensor detection mode.

In the arrangement with two light sensors and one thermal infrared sensor, the single sensor detection mode and single sensor non possibility mode are in effect while in the arrangement with two heat sensors and one light sensor, single sensor detection mode is available but single sensor non-declaration is not practical as any heat sensor may declare the presence of fire.

Experiments were performed in dimly lit environment to minimize the risk of unwanted source seeking. While using the single sensor non declaration mode is a deterrent against a false alarm, as the algorithm requires the heat to be present in declarations but having multiple light sources increases the source finding time.

9.2 The Target

Thermal Infrared Heat Lamp by HASKELLITE ® was used as the fire source as it was not safe to light a fire in the lab. The source was 375 Watt, 120-130 Volts with a clear head and medium base.

Figure 9. 1 Thermal Infrared light bulb used as fire source

This light bulb produces high temperatures and light values and was most suitable among the available choices.

The light bulb was mounted on a holder and was carefully placed at the same height from the ground as that of the sensors to maximize the possibility of detection.

9.3 Testing Scenarios

The following scenarios were tested with both sensor arrangements

1. Target present in plain sight not directly in front of the robot
2. Target present behind a flat obstacle
3. Target present behind a set of obstacles making a concave shape
4. Target present behind a convex obstacle
5. Target present behind a flat obstacle with a reflective wall present on the side
6. Target present behind a flat obstacle with a non-reflective wall on the side
7. No target present

9.4 Sensor arrangement with two light and one temperature sensor:

9.4.1 Target present in plain sight not directly present in front of the robot

This is the simplest scenario where the target was in plain sight of the robot The robot started its movement in a sinusoidal motion but as it detected elevated levels of light it began target tracking. The following waveform charts describe the approach, sensor readings, distance from obstacles, light values and the detection mode that was responsible for declaration of fire incident.

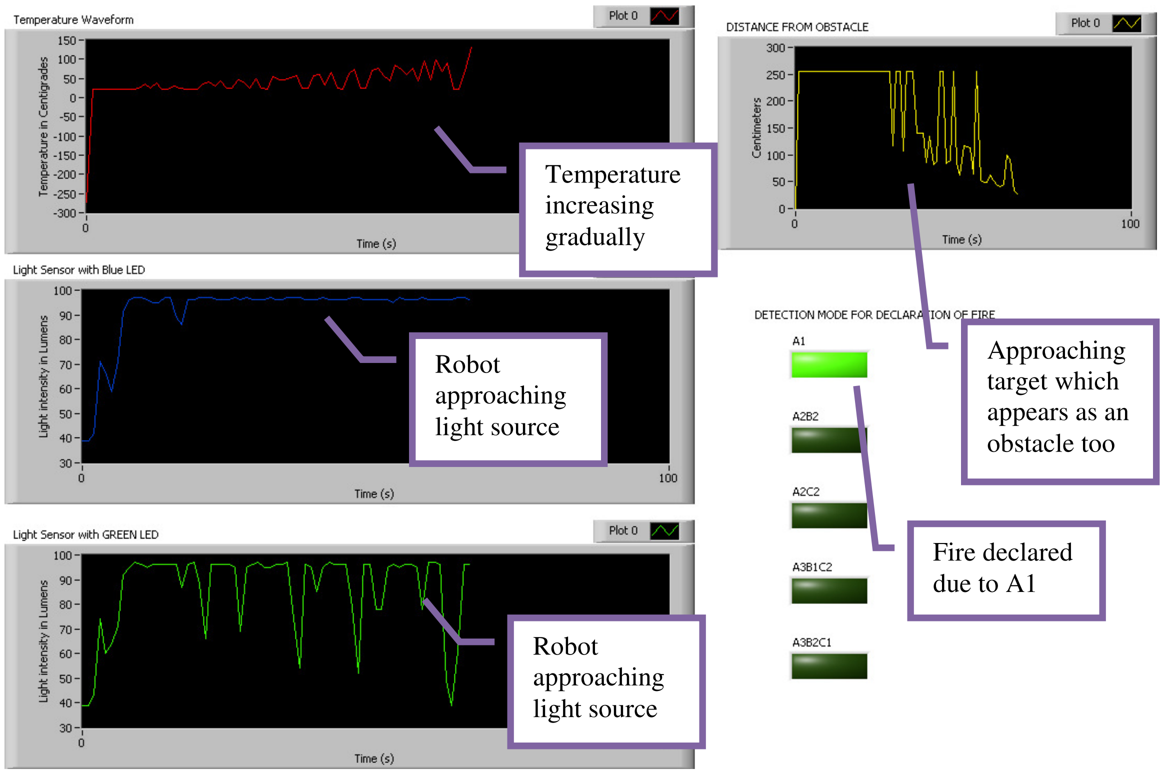


Figure 9. 2 Robot approach GUI values with no obstacle

Figure 9. 3 Sinusoidal movement of the robot

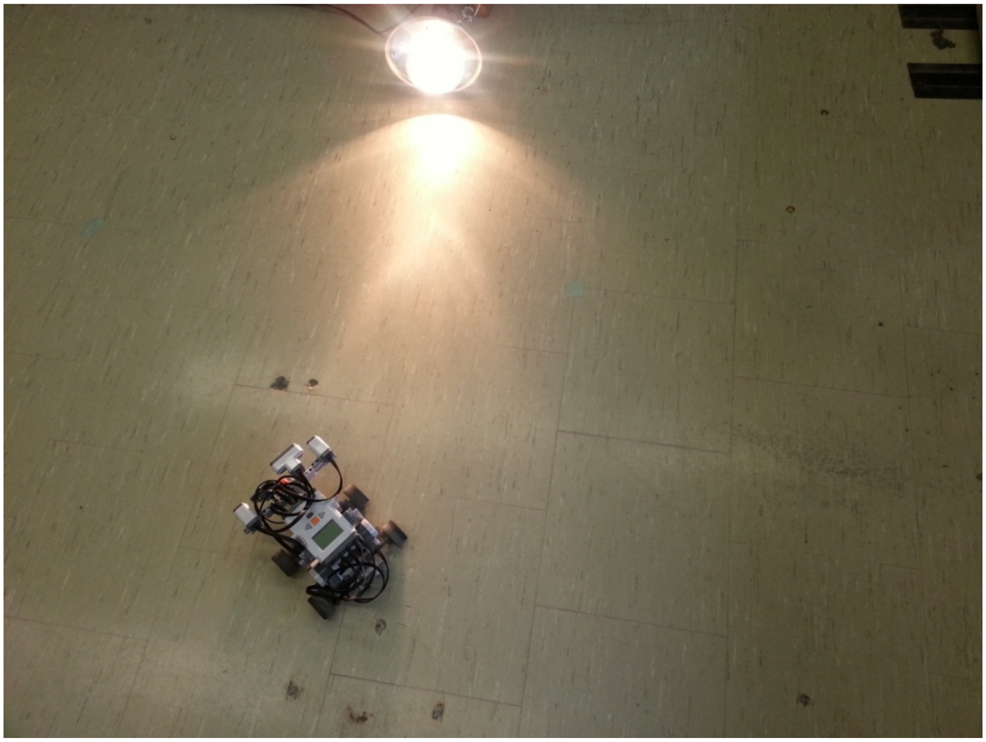


Figure 9. 4 Robot detected elevated light and navigating towards it

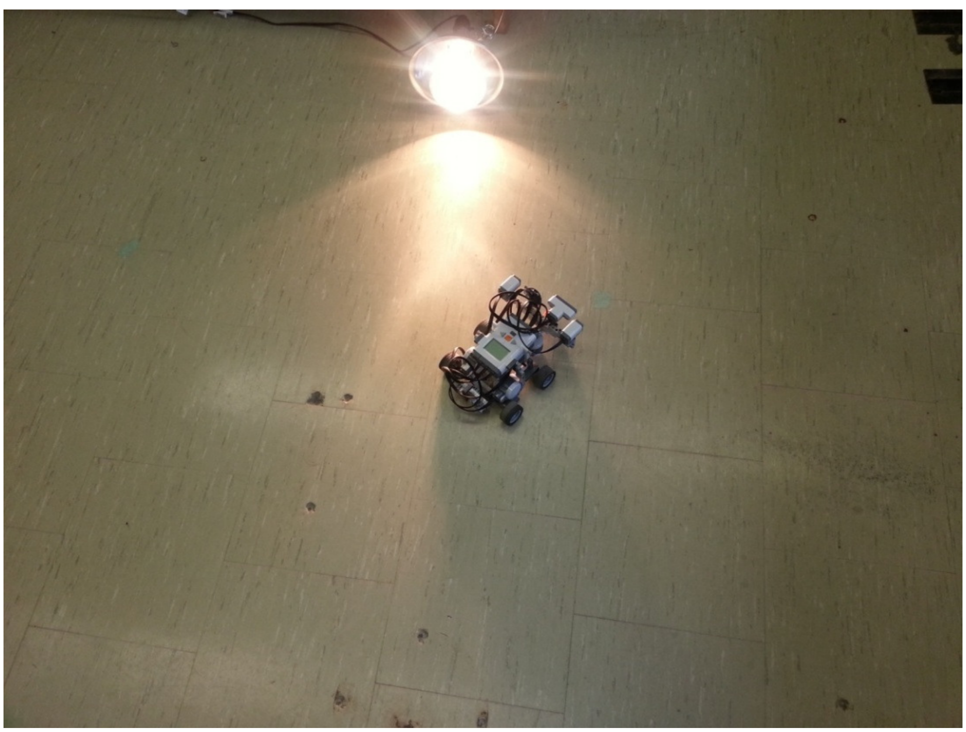


Figure 9. 5 Robot approaching the target

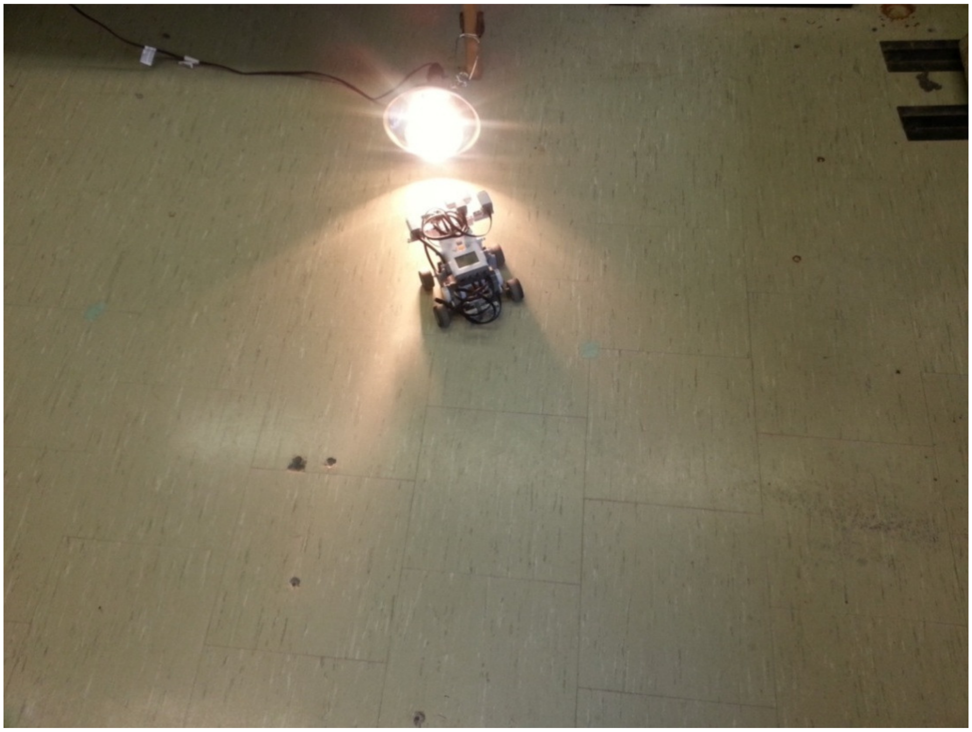


Figure 9. 6 Sensor readings are high but the target is not declared yet

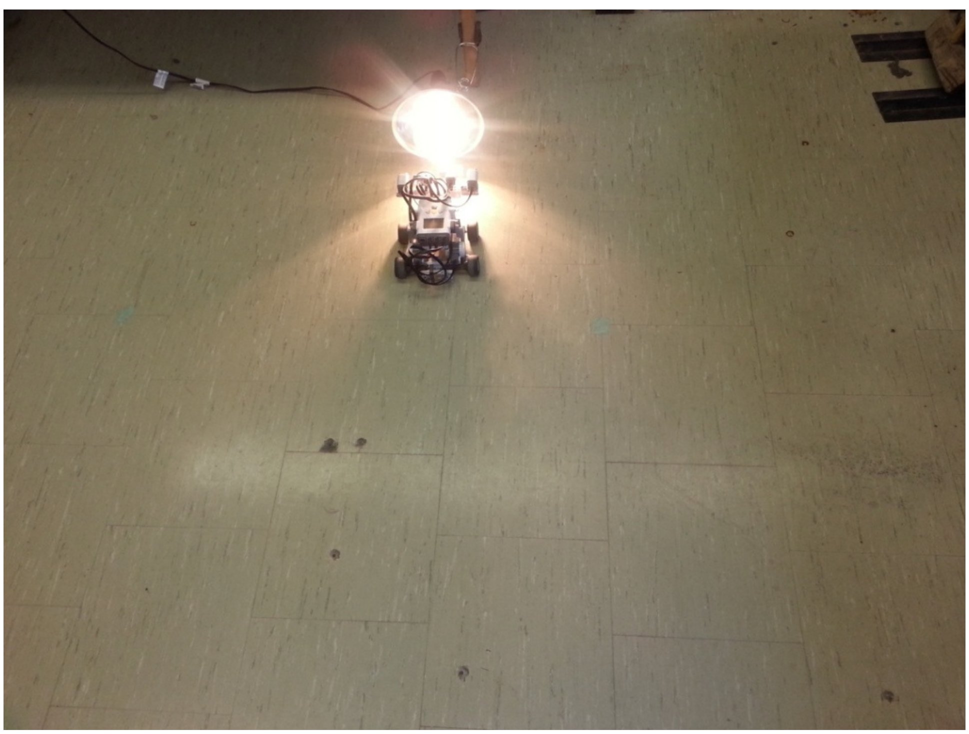


Figure 9. 7 Target declaration using modified voting logic

Figures 9.3 to 9.7 describe the robot motion towards the target. In Figure 9.3 Robot does not observe the target but there is a higher value of light towards its right. The sinusoidal movement allowed it to detect that value for the first time and then the sensor value comparison brought it to the source. At that point, in Figure 9.7 the fire declaration algorithm allowed the robot to positively identify the presence of fire.

At the same time the Figure 9.2 supports the movement by providing the readings for each time. It can be clearly seen that the light values increase gradually but also a shift in the two peak values from the two light sensors may be seen which is the guiding mechanism of the robot. It can also be observed that the declaration of fire occurred because of the declaration mode A1 which means that this time the sensor was directly in front of the source and other sensors were not required to participate in the decision making process. Meanwhile the distance to the obstacle can be observed reducing with every cycle since the robot identifies he light bulb as an obstacle as well. Because of the powerful light and heat combination the fire is declared in more than 24 cm which is the minimum allowable distance of the robot with an obstacle in accordance with the LabVIEW VI governing this source seeking.

9.4.2 Target present behind a flat obstacle

The same VI for the same sensor arrangement is used for all the experiments in this section. In this case the target is present behind an obstacle that is flat.

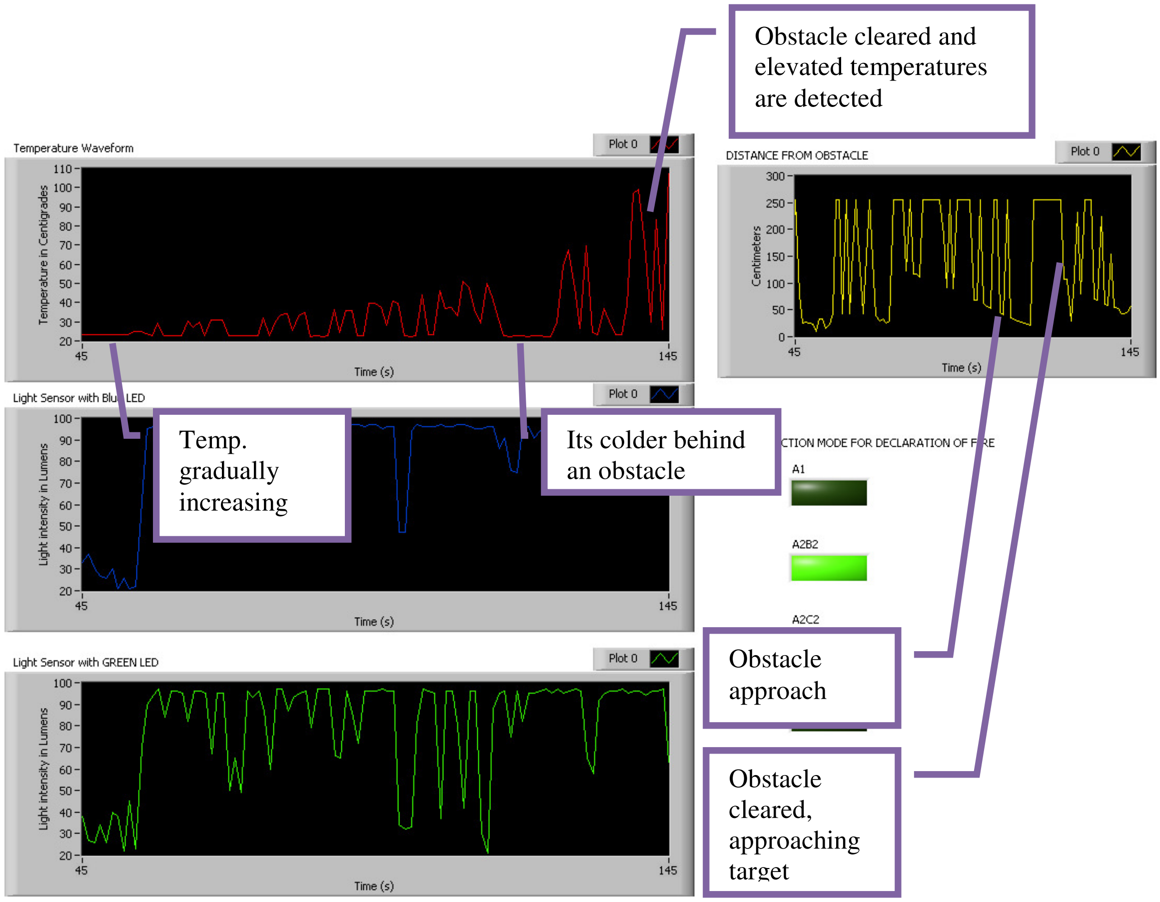


Figure 9. 8 Target behind a flat obstacle

In this case the target was present behind a flat obstacle. It can be observed from the temperature graph against time that the temperatures are at the room level in the first ten seconds but the light values differ. That leads the robot to move and follow the light. Once the source is detected it can be observed that whenever the robot goes behind an obstacle, the temperature values fall to the room temperature. Also when there is no obstacle in sight the Sonar sensor returns the value of 255cm for the distance hence the graph never goes over 255 for the proximity sensor.

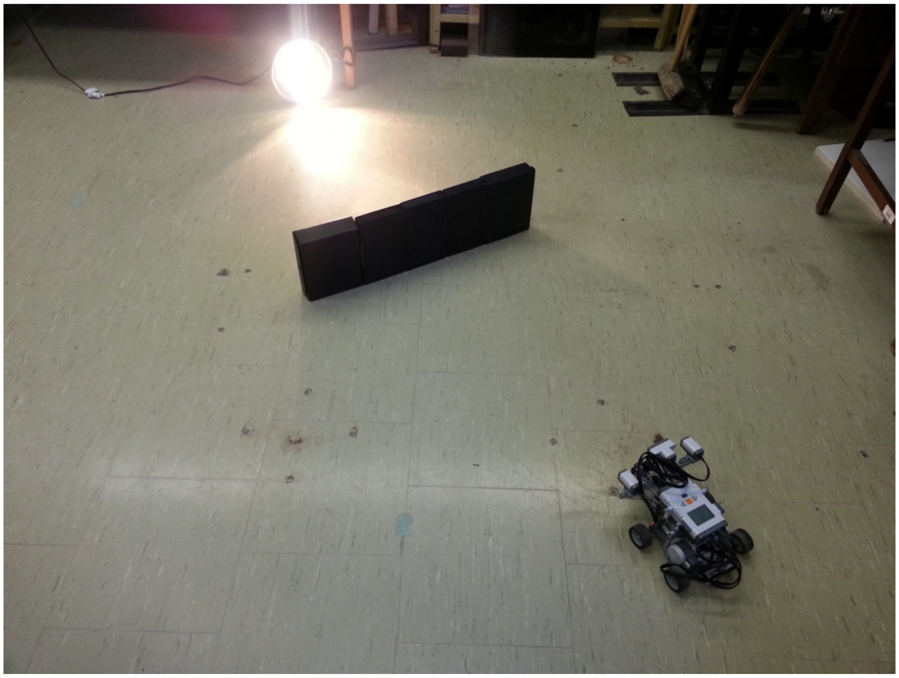


Figure 9. 9 Initial approach behind a flat obstacle

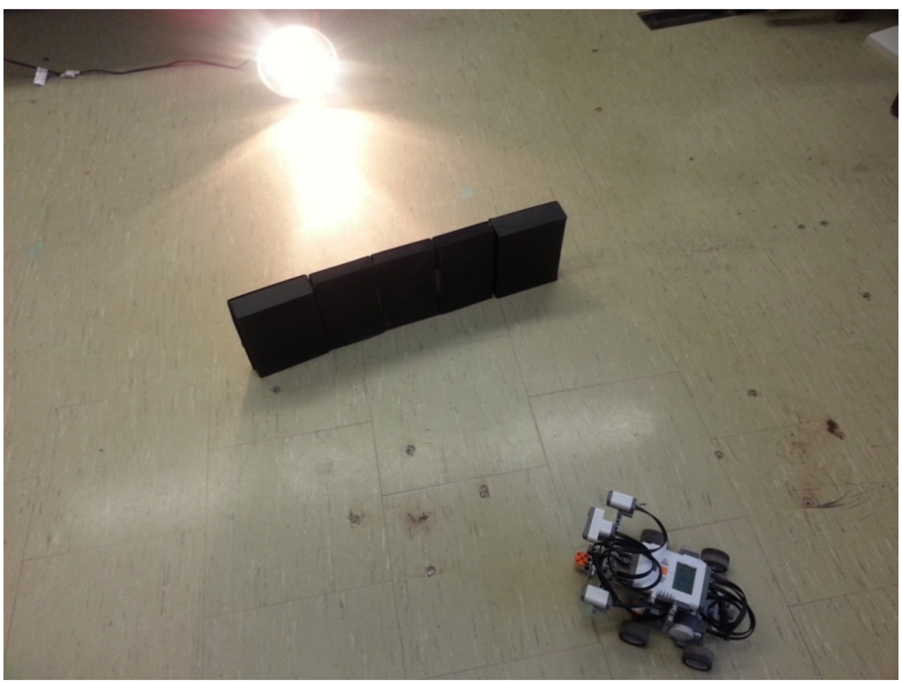


Figure 9. 10 Sinusoidal movement because of low light values

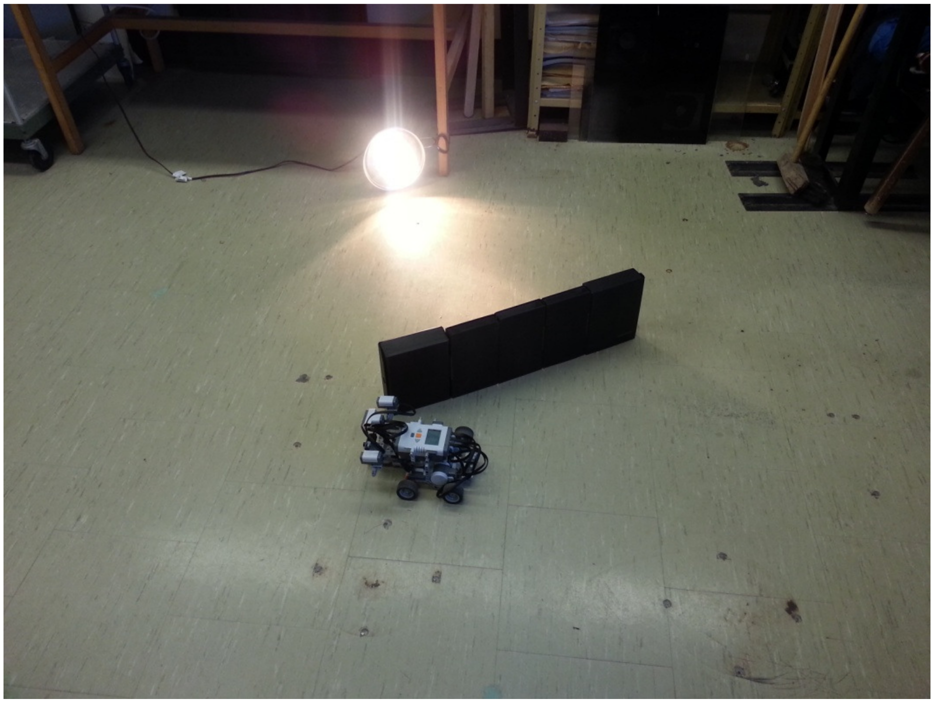


Figure 9. 11 Going around the obstacle

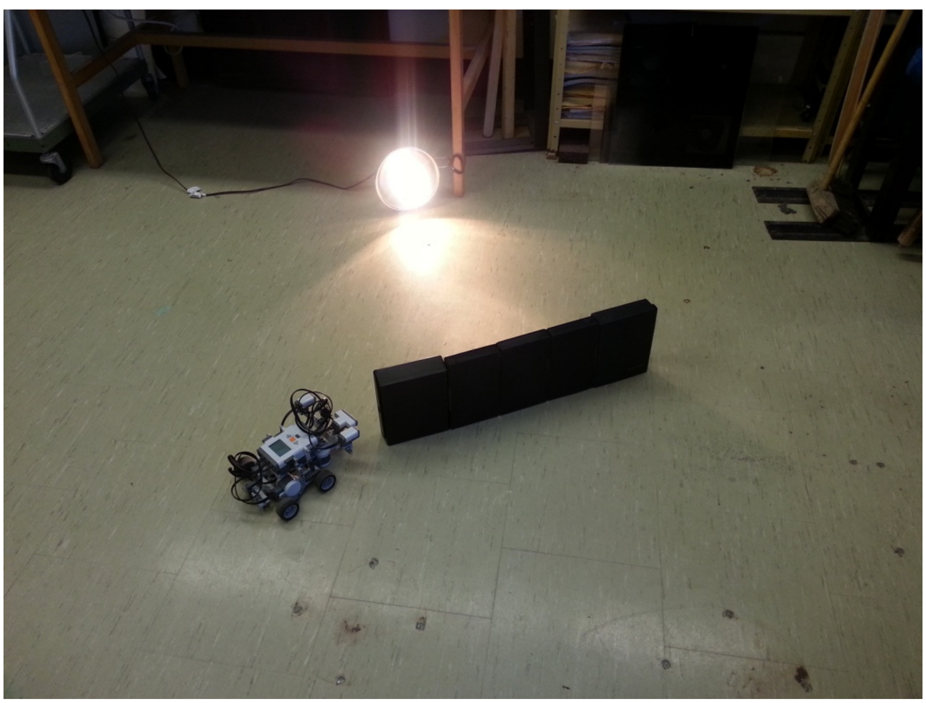


Figure 9. 12 Clearing the obstacle

Figure 9. 13 Target approach

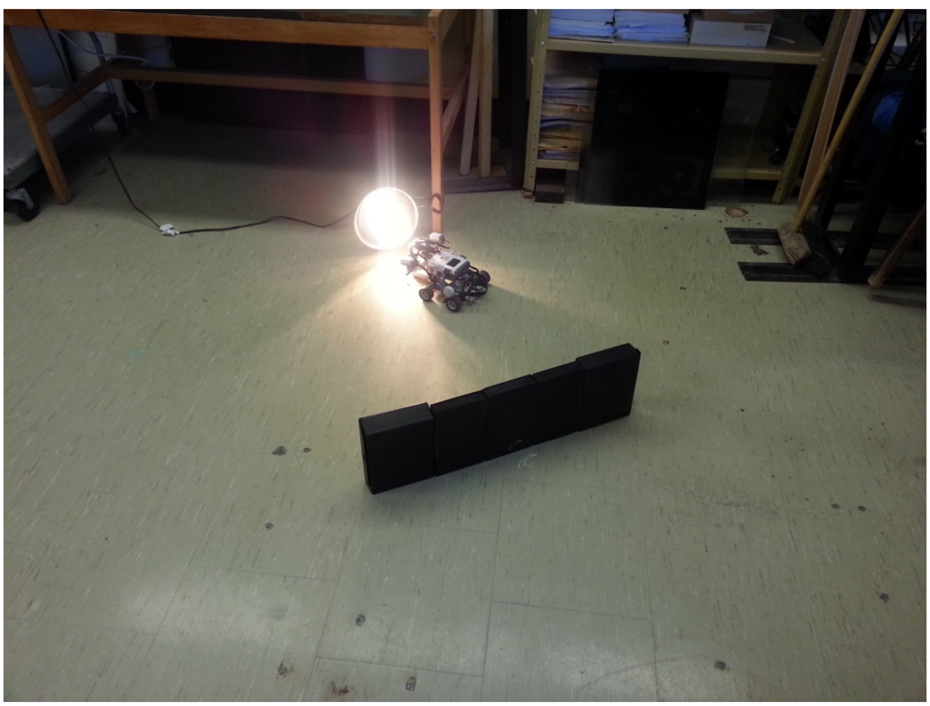


Figure 9. 14 Target (Source) declaration with detection mode A_2B_2

It was also observed that when the robot crosses the obstacle from the right side, it tends to touch and sometimes knock over the obstacle. Even though it does not affect the working of the robot, it is not desirable. To overcome this challenge, the backing up time was increased to 1 second (1000 ms) with results

9.4.3 Target present behind a concave obstacle

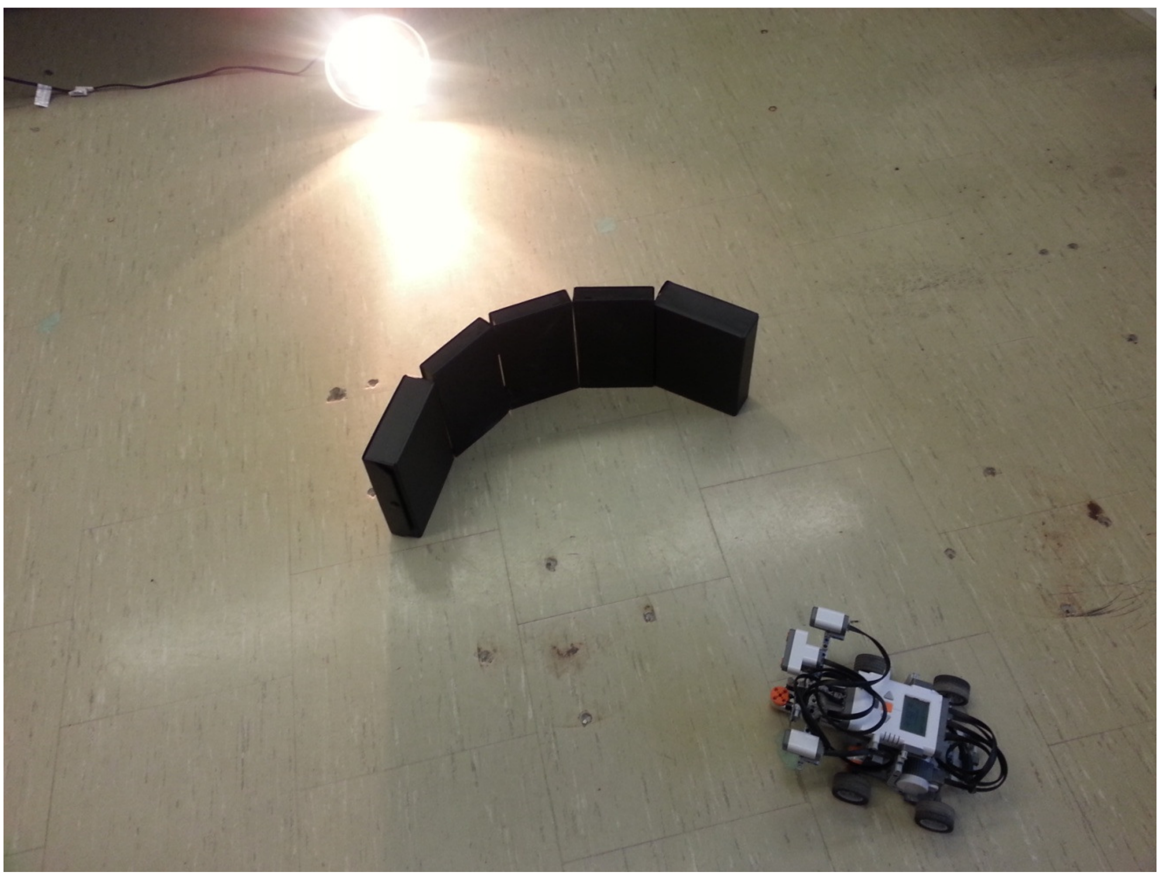


Figure 9. 15 Target present behind a concave obstacle

It was observed that while approaching the source with concave shaped obstacles, the directional backing up was not successful and the robot got stuck 3 times out of 10.

The VI was modified slightly to allow the robot to back up straight for 1 second and restart the approach towards the target. This allowed the robot enough time to get out of the concave obstacle and find the light or heat signal to follow.

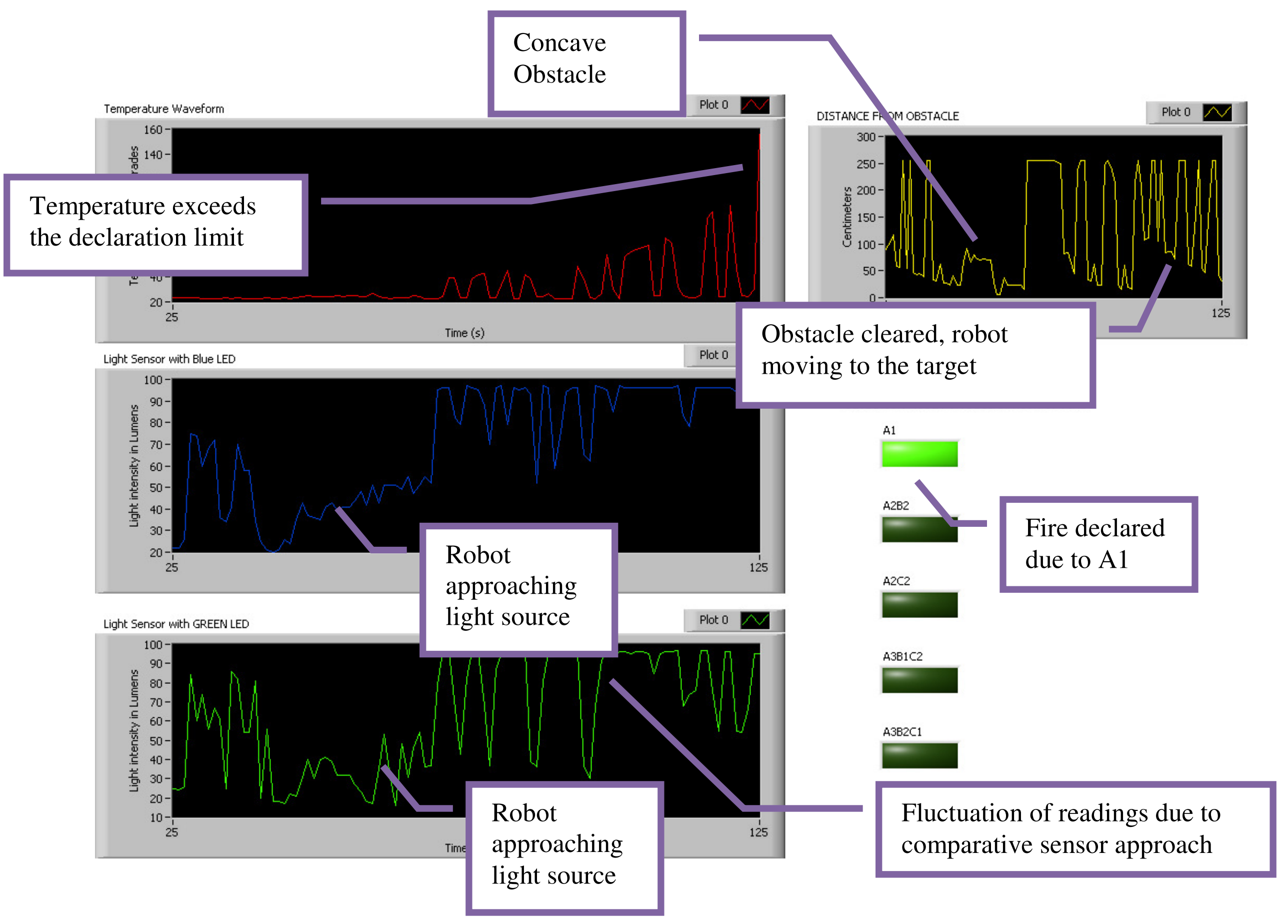


Figure 9. 16   Concave obstacle target detected with detection mode A_1

9.4.4 Target present behind a convex obstacle

Finding a target behind a convex obstacle was the easiest of all the scenarios.

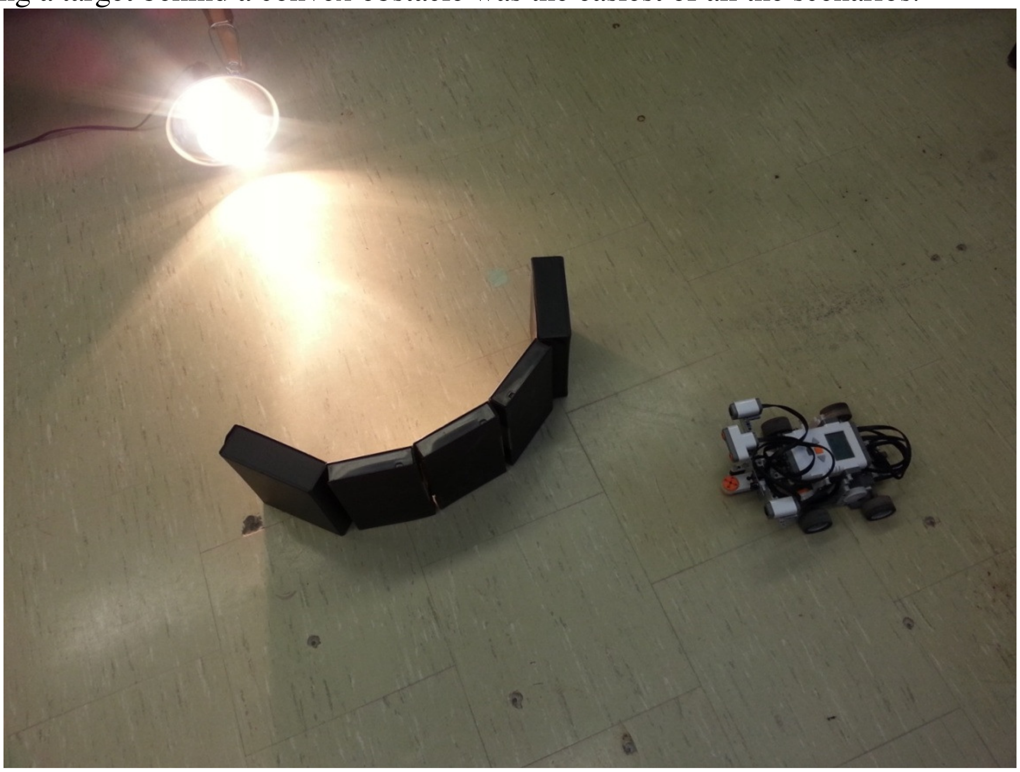


Figure 9. 17 Target behind a convex obstacle

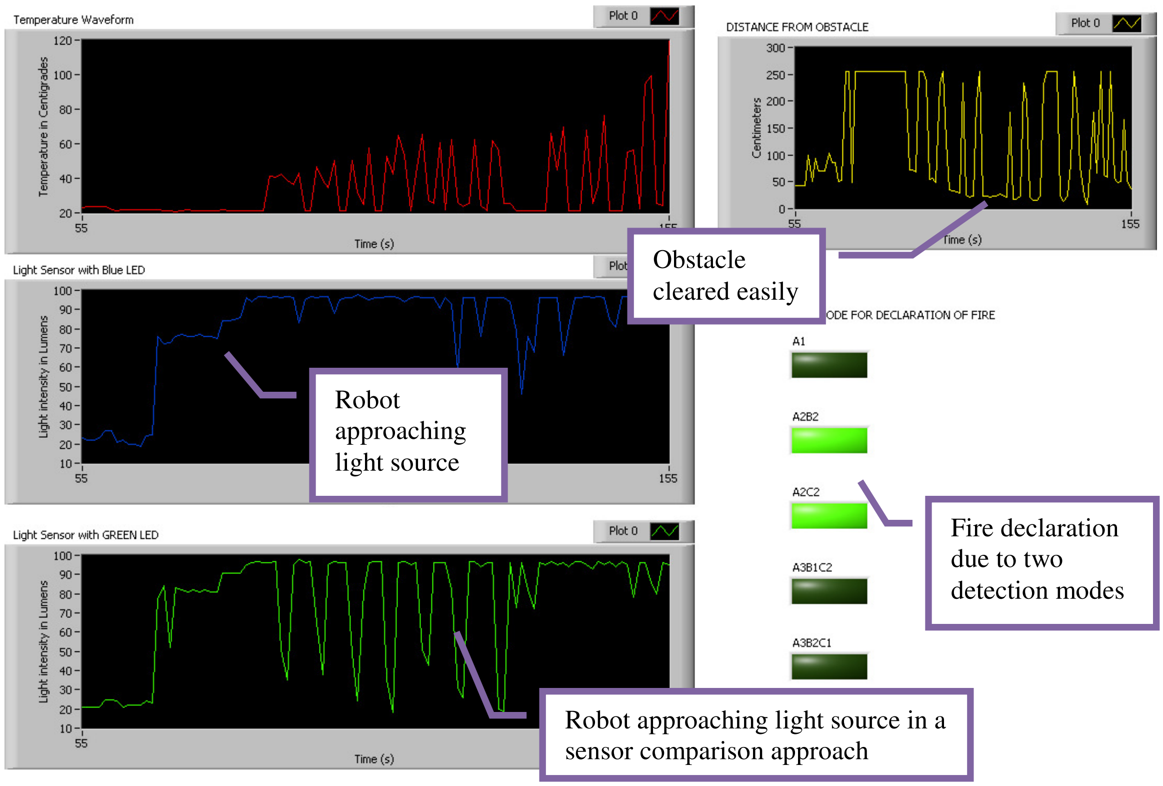


Figure 9. 18 Target declaration behind a convex obstacle with two detection modes

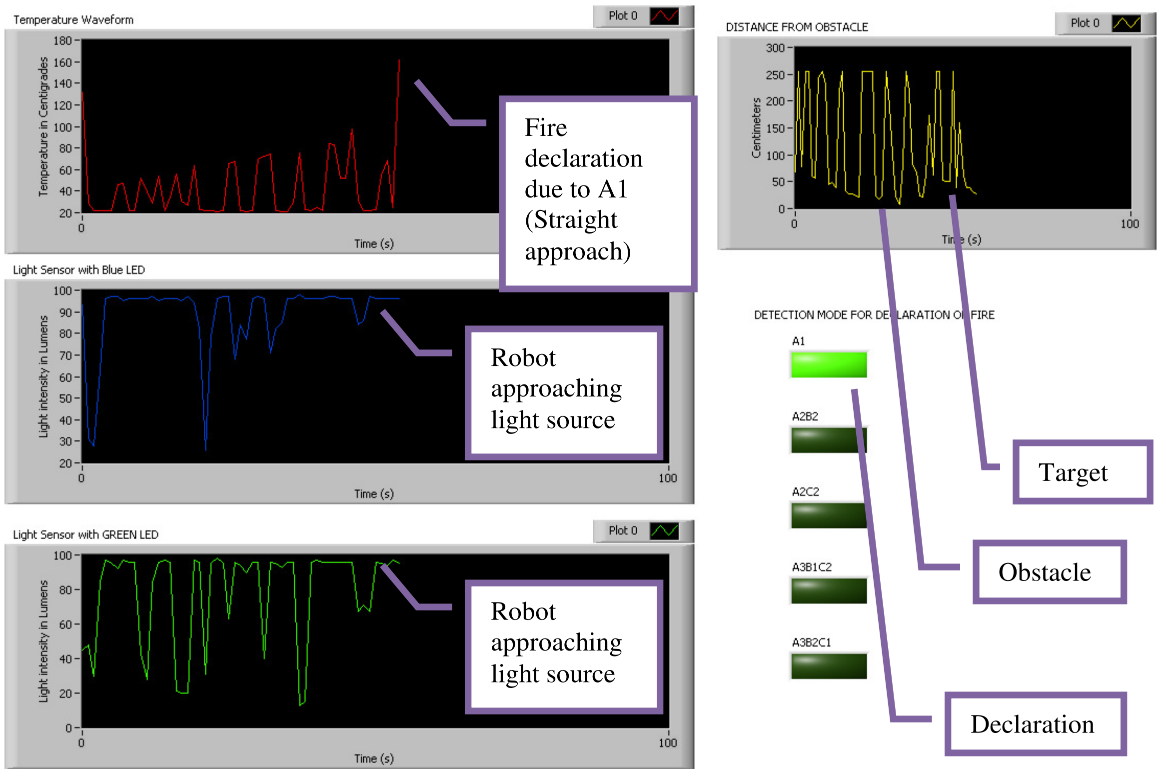


Figure 9. 19 Another case with different detection mode for target present behind a convex obstacle

9.4.5 Target present behind a flat obstacle with a reflective wall on one side

This is one of the most interesting results. Looking at the graphs closely it can be observed that elevated temperatures and light values were detected starting the timeslot of 46 seconds. Then the temperature and light values abruptly come to a lower level. At that point there is a little sinusoidal-like variation in the light intensity values and temperatures. Then the values increase and the robot follows a familiar approach until declaration of the fire, which, in this case, happens to be a single sensor declaration mode identified as A1.

In this particular case the robot started its approach towards the wall after the detection of elevated light values, as the wall was reflecting light. As the robot approached the wall the obstacle avoidance mechanism kicked in. In the obstacle avoidance as there is gradient of light comparison also included, therefore the robot faced the source while backing up. Right from there, the case practically becomes as described in the first scenario, i.e. the source in plain sight of the robot.

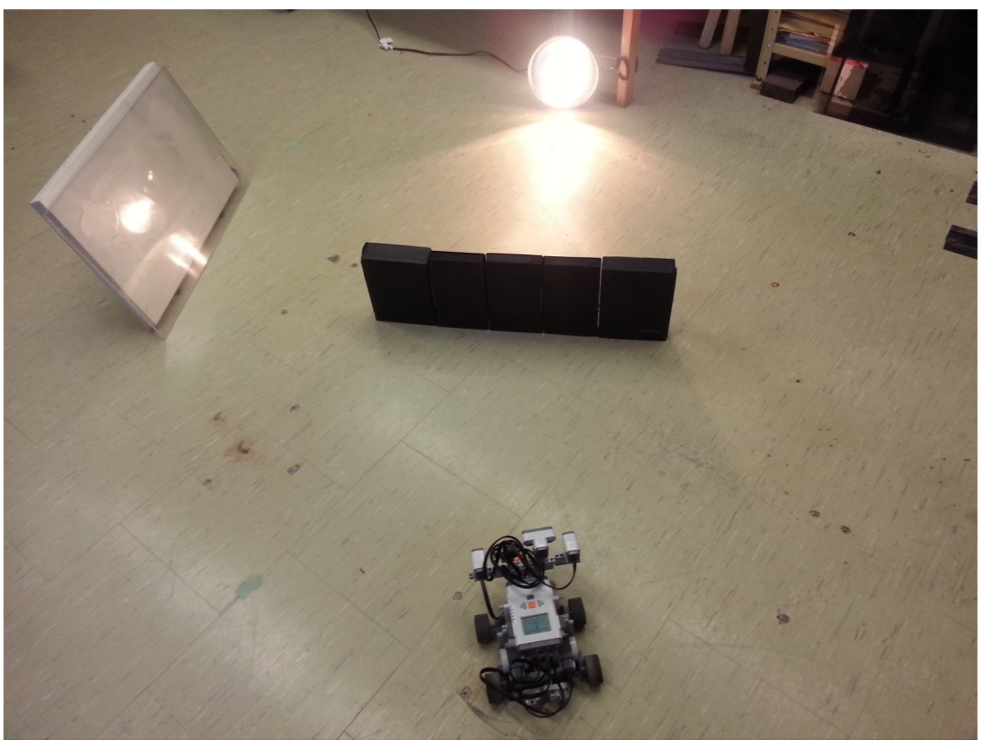


Figure 9. 20 Flat obstacle with a reflective wall

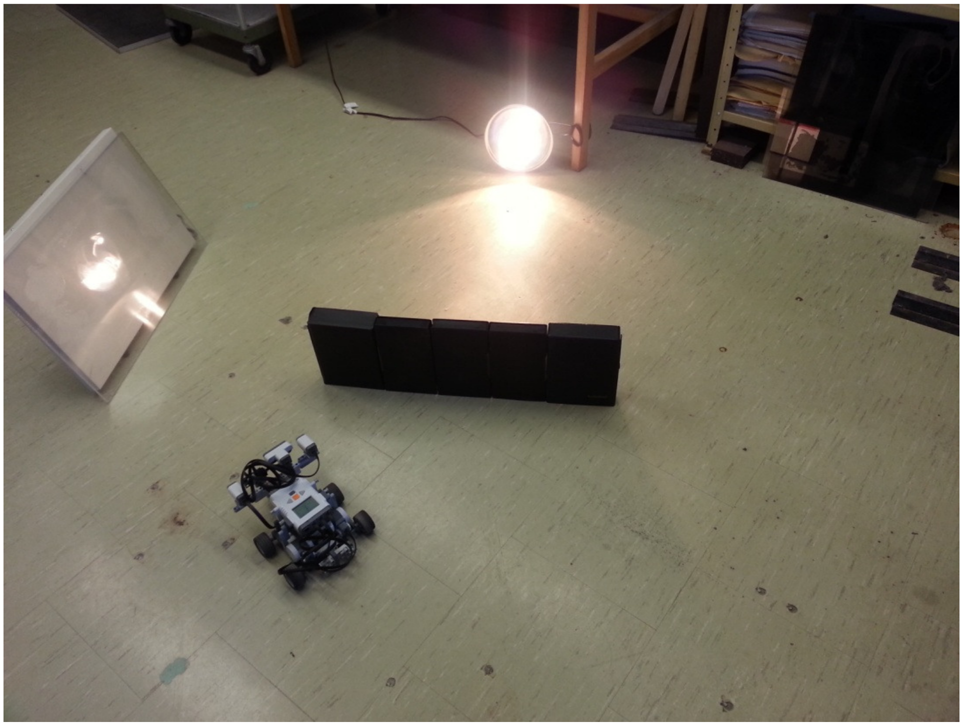


Figure 9. 21 Robot follows the reflected light from the obstacle

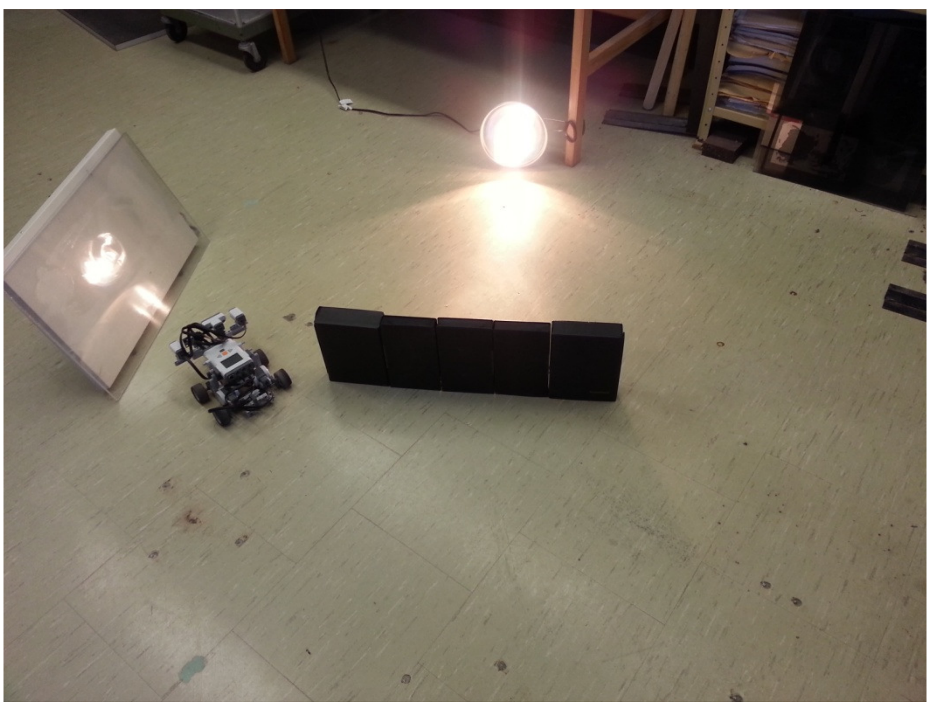


Figure 9. 22 Robot approaches the reflected light from the obstacle

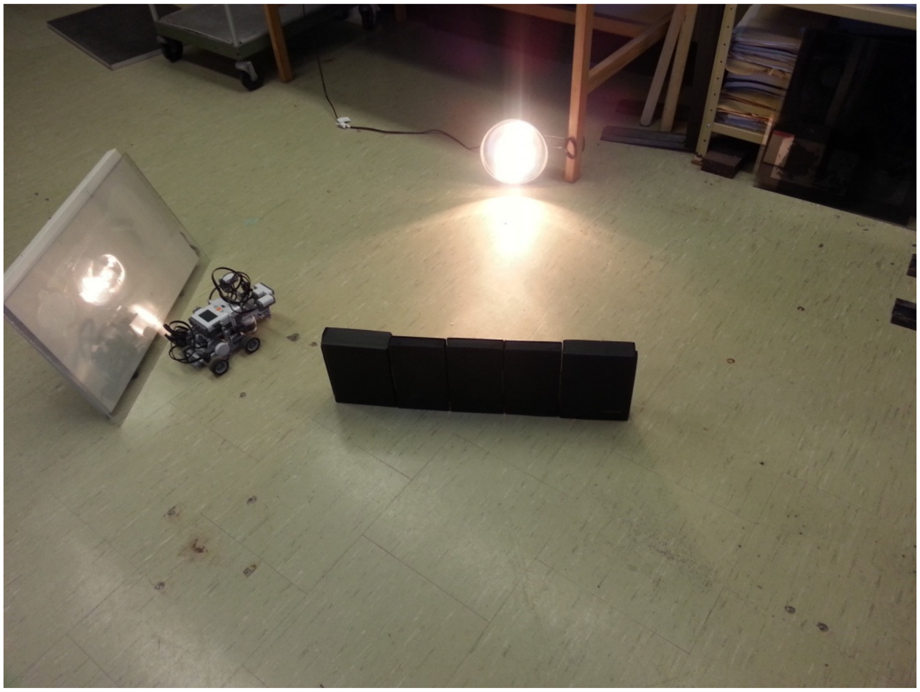


Figure 9. 23 Robot detects higher values of light and temperature as it turns back facing towards a higher value of light

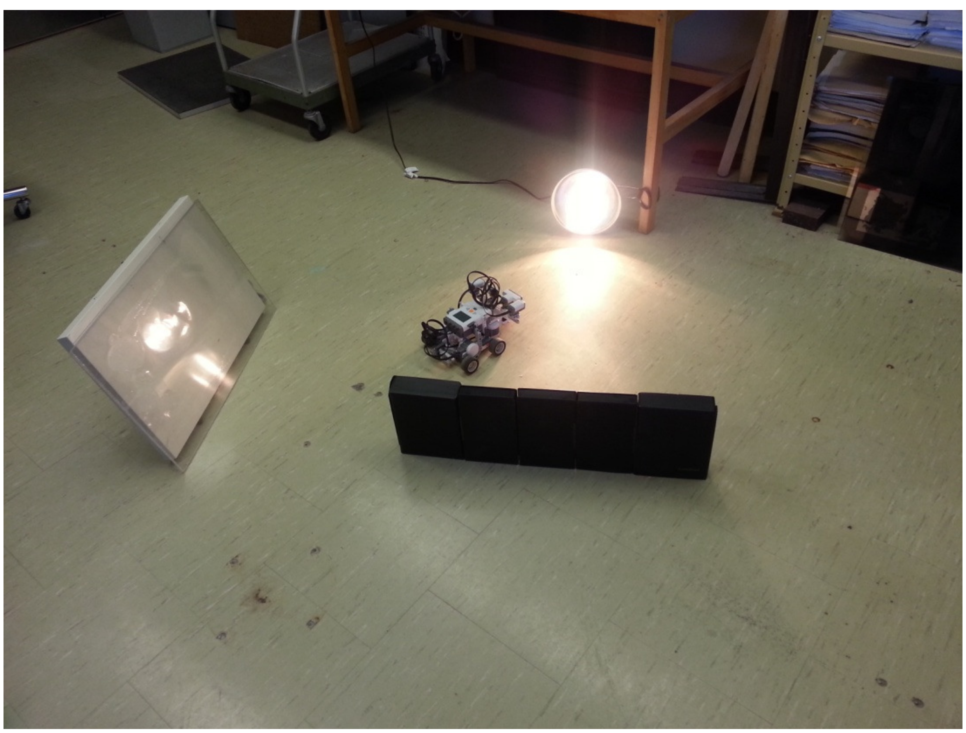


Figure 9. 24 Robot clears the obstacle and is following the correct source

Figure 9. 25 : Source (Target) confirmation be modified voting logic

As described earlier this case is where the obstacle is present with a reflective wall on one side. The following figure explains the process. Figure 9.27 explains the readings from thermal infrared sensor

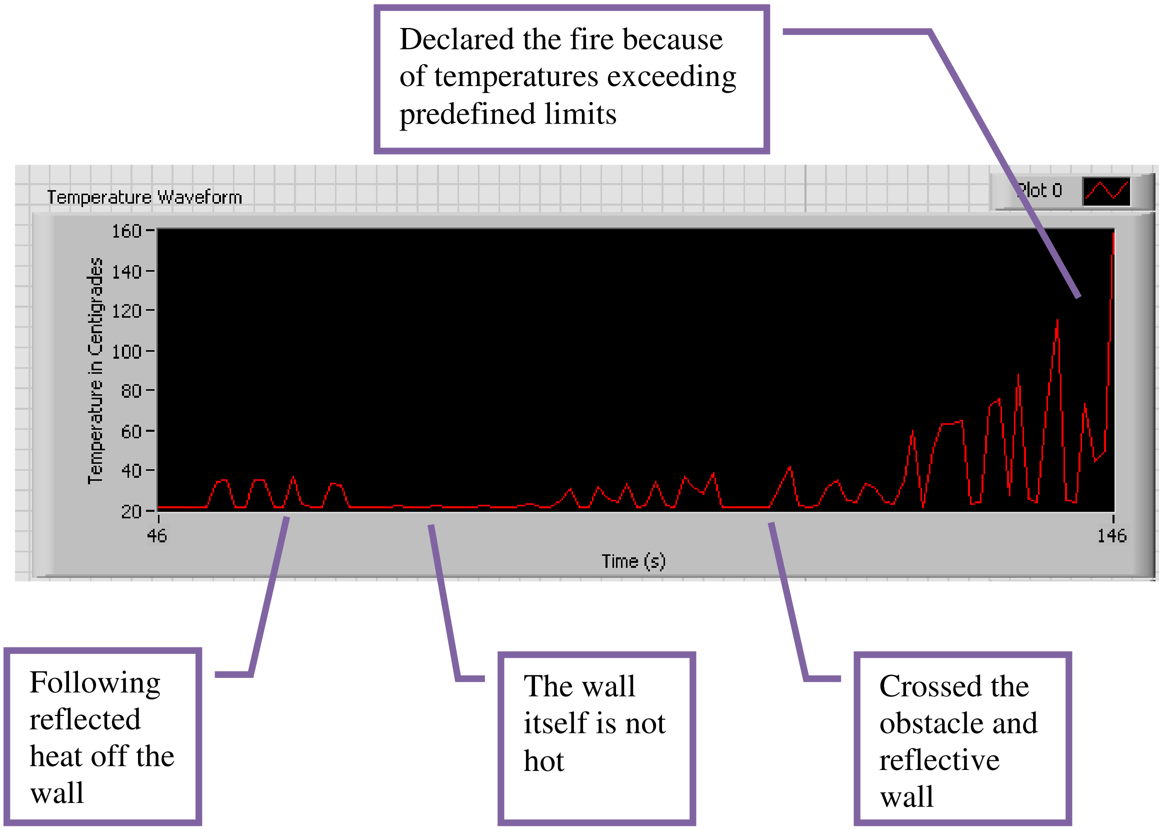


Figure 9. 26   An explanation of the thermal readings and milestones

If the Sonar waveform is closely examined in the following figure it can be clearly seen that the robot follows the reflected light, detects reflected wall as an obstacle, which is where its reading dips down to a lower value. Again the lower values are seen because of the actual obstacle as it passes by it. While it performs obstacle avoidance it faces the actual source of light and heat and follows it to declare a fire incident.