International Journal of Recent Technology and Engineering (IJRTE)
ISSN: 2277-3878 (Online), Volume-8, Issue-1, May 2019

A Stochastic Search Algorithm for Fire Rescue Assistance

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***Abstract:** This paper explores the use of mobile robot to assist in finding humans/pet in residence or workplace during fire accidents. Early detection of life and their location coordinates play a crucial role on number of causalities in fire rescue operation. The proposed robot is an autonomous robot that searches the building for human life by following a predetermined path while live streaming video of the accident zone. This paper proposes a novel search algorithm, Follow Hop Search algorithm (FHS) for early and easy detection of lives in poor lighting, smoke filled and watery environment of fire accidents. We combined maze solving algorithm along with building plan analysis and the location of properties to facilitate stochastic decision making to determine the Plausible Search Path (PSP). The developed system integrates existing fire alert system with a fully functional search robot programmed with the SHR algorithm to improve efficiency of the rescue operation.*

***Index terms:** Early detection, fire accidents, Fire alert, Rescue assist robot.*

I. INTRODUCTION

Autonomous robotic vehicles can be used to assist in handling a variety of dangerous and lifesaving tasks, like disaster search and rescue, environmental monitoring, resource exploration, patrols, etc. The National Crime Records Bureau Data (NCRB) reports that, on an average, about 25,000 persons die every year (approx 63 death/day) due to fires and related causes in India. Accidental fire ranks third in the causes for unnatural deaths and loss of assets, due to fire is estimated to be almost USD 100 billion per year in India [1]. Since, fire spreads very quickly, doubling in size every minute controlling fire is not easy. It requires early detection of fire, enormous amount of water / river sand and experienced person to handle the fire extinguishers. In most of the incidents availability of the above resources are very less hence it is difficult to control the fire and this in turn causes huge damage. A robust system that helps to detect fire early and alerts the fire brigade about the number of people inside the building will help in reducing the number of fatalities. Generally, automatic sprinkler systems and fire alarm system are deployed to control fire and alert humans during fire accidents.

Revised Manuscript Received on 30 May 2019.
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However each has its own disadvantages. Though Automatic fire sprinkler systems are one of the effective fire protection systems, it fails to detect human / pet trapped inside the fire zone due to the factors like fear, no escape options, fatigue, drowsiness and sleep [2],[3]. A fire alarm system warns people upon detection of fire to evacuate building, alerts the fire brigade, identifies the location of fire and facilitates remote monitoring of a fire within a structure or a building is also deployed in many buildings [4]. However the effectiveness of fire alarm system depends on response of humans to the alarm [5], arrival time of fire brigade at the scene of the fire, availability of fire exit facility etc. The non availability of fire fighting resources is also a major reason for the number of fatalities. Statistics published by [6] quoting National Disaster Response Force and Civil defense, shows a deficiency of 72% in number of fire stations,79% shortage in manpower and 22% shortage in vehicles / devices in India. Vehicular failure/breakdown, heavy traffic conditions, an accident on route to the accident site, distance from the nearest fire station and deficiencies in manpower/vehicles adversely affect the arrival time of the firefighters. These factors hugely affect the number of fatalities. Due to the above reasons the firefighters may arrive late at the accident site. After arrival the biggest decision a fire fighter must make at the site is whether to go offensive (go into the building) or defensive (put out fire from outside). This decision must be quick and correct based on the number of people held up in the building, location of the human, likelihood of life since interior operations might be a great risk to firefighter life and safety [7],[8].

After the considering the need for a robust assist device, we propose an autonomous search robot that

i. Can be deployed by a signal from the existing fire alert systems or manually, to improve the efficiency of the rescue operation
ii. Employs a stochastic approach to determine the search path (PSP) based on building plan, location of properties and maximum likelihood of human/pet presence at a particular location in the building.
iii. Uses a novel search algorithm (FHS) to extensively search the building and simultaneously live stream the accident zone.

The paper is organized as follows; Section II discusses the related literature and the need for a robust assist device in rescue operation. Section III, discusses the determination of the plausible search path, basic design of the mobile bot and the follow hop search algorithm. In section IV the results are discussed.

II. RELATED WORK

Automatic sprinklers save lives and property only when sprinklers are present in the fire area, when fires are large enough to activate sprinklers, when they are operating with sufficient water [9].

The main disadvantage of the water sprinkler / fire alarm system is the time delay between the start of fire to the time of detection. The water sprinkler/ fire alarm uses smoke sensors to detect fire. The location of the detector, distance between the detector and the fire is a major impediment in the early detection of fire [10]. Most of the time fire is detected after it has spread to a wide area.

To overcome this disadvantage, the use of camera & image processing to detect fire is gaining importance [11], [12]. While the images captured by the camera are used to detect fire and raise an alarm, it does not assist the fire fighters in identifying the number of persons or their location inside the building. Some industries use the manual or automated head count to find the number of people inside the building. Though this gives the count of people caught inside the building, they do not provide any information on the location of the persons. Therefore a search robot which provides the fire fighting personnel about the number of lives and their location will improve the chances of evacuating them.

Fast flow control algorithms for evacuation during fire which integrates positioning of doors; orientation of path, augmented reality, and shortest path-finding algorithms to achieve efficient and effective evacuation in real time is discussed in [13]. Analysis of Building information modeling (BIM), visibility graph (VG) and medial axis transform (MAT) is used to help the decision making for response operations in [14]. A fire evacuation, rescue and recovery system based on a near real-time intelligent blast damage assessment (BDA) / target vulnerability assessment (TVA) tool and on-line ERR-related optimization techniques is proposed in [15]. The above methods assist in the evacuation process in large indoor structures but do not aid in the search and localization of victims. Available path finding algorithm like the Dijkstra algorithm, greedy algorithm, A* Algorithm find the shortest path from the root node to the destination. Shortest distance algorithms tend to be inefficient in search operations there are many chances of missing some essential corridors / balcony / board rooms in the buildings and are more time consuming if all nodes are given equal priority. Back tracking and multiple search options are mandatory for search operations when the target location is not known [16-21]. Hence we propose an assist device which integrates a dynamic search algorithm (FHS) with a most feasible search path and existing alert devices to extensively search the building and provide information for the rescue operation.

III. THE PROPOSED METHOD

The proposed mobile robot is a self-operating search machine that follows the predetermined search path on the floor. The search path is determined by choosing any one of the maze solving algorithms namely LNR, LRN, RNL, RLN, NLR, NRL based on building plan analysis and the location of properties inside the search area. The multiple **Plausible search paths (PSP)** are determined based on the maximum coverage of required search area in minimum time. Before deployment, the robot must be trained to follow all the PSPs on the floor to reach the destination by using the SHR algorithm. This is done by storing the PSP track details in the memory of the robot. Upon deployment, it follows the PSP very accurately based on the stored coordinates. If the robot is not trained for the building under consideration it can also be manually driven by using a Bluetooth or a remote control. If an obstacle is detected in the path, the robot automatically backtracks and shifts to the nearest alternate track. The three phases of development are

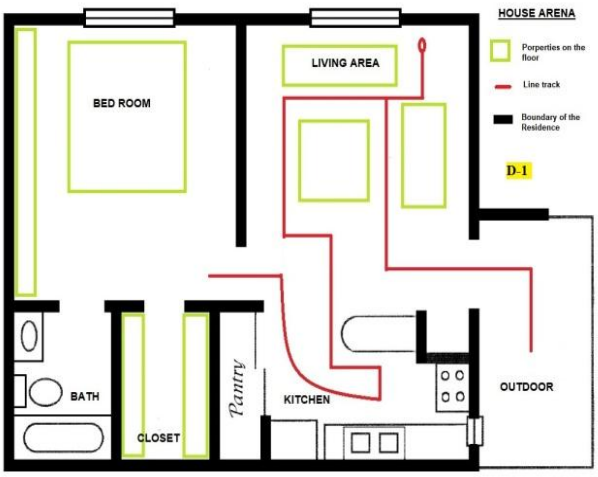
a. Finding the **Plausible Search Paths**
b. Design of the robot and integration with existing fire alert system
c. Implementation of the Search Hop Rescue Algorithm

A. Finding the Plausible Search Paths

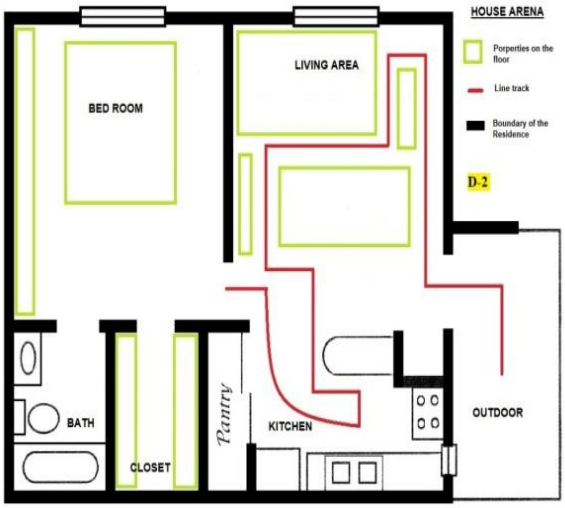
Shortest path finding algorithms like the Djikstra algorithm, heuristic/ greedy algorithm, A* Algorithm can be used fire rescue operations only when the location of the human/pet is known. They can be used to find the shortest path between a said node and destination but do not promise maximum coverage of search area and consume more time if the path is blocked by obstacles. So the unique algorithm is proposed in the paper to maximize the probability of finding a trapped human/pet inside the building in a fire accident scenario.The floor plan and the location of the properties inside the building are prerequisites to determine the search path. Based on the data, the robot is first programmed with a predefined path with maximum search area coverage. Then the path is traced using all the maze solving algorithms namely LNR, LRN, RNL, RLN, NLR, NRL. Then the best path and the priority mode are chosen based on the maximum coverage of search area in minimum time. This path is called as the PSP. An example of a basic floor plan of a house with the location of properties is shown in figure 1. Table 1 provides the time taken by each algorithm to search the said area. Based on the values we see that LNR algorithm provides optimal search time for the D5, RLN provides optimal search time for D1, D2 and & RLN for D3, D4.

Algorithm	D1 (57 feet)		D2 (56 feet)		D3 (81 feet)		D4 (69 feet)		D5 (39 feet)
	Room 1 (Living) (38feet)	Room 2 (Kitchen) (19 feet)	Room 1 (Living) (39feet)	Room 2 (Kitchen) (20feet)	Room 3 (Bedroom) (53feet)	Room 4 (Bath& closet) (28 feet)	Room 3 (Bedroom) (43feet)	Room 4 (Bath& closet) (26feet)	Room2 (Kitchen) (39feet)
	Time in seconds								
LNR	9.3	5.2	9.1	5.2	13.7	9.3	10.6	8.1	***9.0***
LRN	9.1	4.3	9.0	5.1	12.9	9.4	12.1	7.4	9.7
RNL	***8.1***	***4.2***	8.9	***4.5***	***10.7***	8.7	12.5	7.9	10.7
RLN	8.8	4.6	***8.2***	4.7	12.6	***6.6***	***9.3***	***6.4***	10.1
NLR	9.1	4.9	9.1	5.1	11.4	7.8	10.2	7.1	11.4
NRL	8.9	5.1	9.4	5.0	12.8	8.4	11.6	7.5	11.1

Table 1: Distance travelled Vs Time taken for the six priority algorithm



(i)



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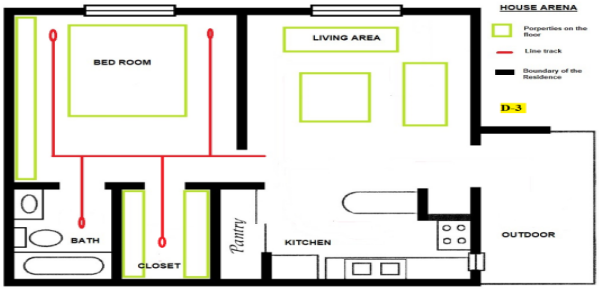

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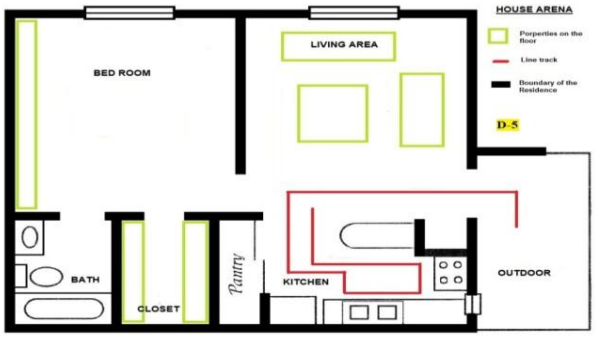

(v)

Fig.1 (i, ii, ii, iv, v) Various track plots for different room arrangements

B. Design of the robot and integration with existing fire alert system

In order to improve the efficiency of the rescue operation and overcome the disadvantages of the stand alone water sprinkler and fire alarm system the proposed method integrates the existing facilities like the camera system used for detecting fire and/or alarm system as shown in fig.2. The trigger sent from the monitoring system / fire alarm / manual is used to deploy the robot. The robot can also be deployed manually on detection of fire and controlled through Bluetooth/remote. The Mobile Bot consists of Chassis, Sensor, Motor driver, Controller, Actuators (Motors and Wheels) and Battery. The basic block diagram of robot is shown in Fig.3. Chassis is the physical structure on which the electronic and mechanical parts are mounted. It is designed with aerodynamic structure and sufficiently large area to provide ample space to accommodate all necessary parts. The chassis is selected based on the weight, load requirements, heat withstanding capacity and ruggedness.An ultrasonic sensor is interfaced with the controller, to detect obstacles in the path as the environment may be unruly due to the rush of evacuation process. The robot is enclosed in an acrylic body/box to protect it from stampede and heat. Acrylic sheet of 5mm thickness can withstand heat up to120° C.

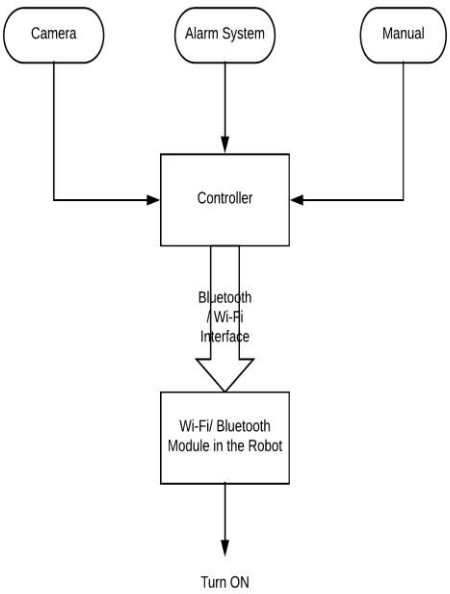

Fig.2 Integration of existing fire alert systems to the proposed robot.

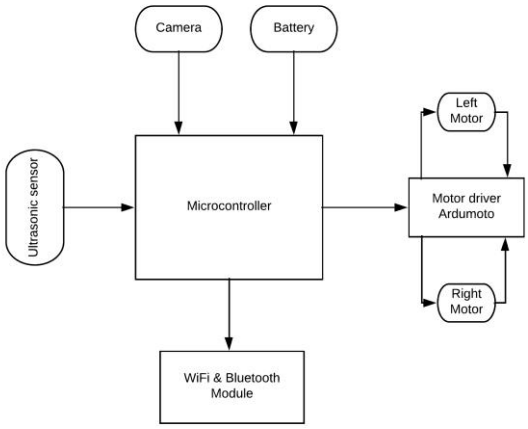

Fig.3 Block Diagram of the Mobile Robot

It follows the correct path with the help of right and left motor rotation coordinates. The coordinates are stored in the memory in terms of "Number of rotations in each motor". A steering mechanism is used to steer the robot on the predetermined track and stay on it. The driver powers the motors according to the control inputs received from the controller as discussed in [8]. Two micro brushed DC gears motors (right motor & left motor) which operate at 6V are used. The motor is selected based on the weight of the robot and torque required. This motor can operate with stall torque at 6V is 9oz with 1000 rpm. The stall current required is 1600mA.The Ardumoto motor driver shield can be used to control the DC motors**.** Based on the two input signals IN1, IN2 the motor can operate in any one of four modes such as CW, CCW, short brake and stop mode. It has a filtering capacitor on both supply lines. Caster wheels are used to support at the front part.

The dimensions of the wheels are 142*19mm. The wheels give perfect clearance between the body and the ground. Turning angle of the robot depends mainly on the speed and motor breaking. If the turning angle is larger, then efficient motor breaking mechanism is required for greater speed.

Arduino Uno board is chosen as the hardware platform to control the entire system because of its low cost, easy to programming, Open source & extensible software able to run on multiple operating systems (Windows, Macintosh OSX, and Linux). The controller receives signals from the sensors, processes the information, controls the motor driver accordingly and simultaneously the camera streaming and live GPS location coordinates are sent. The robot is made of water proof material because it may be exposed to water from automatic water sprinklers or water from fire fighters.

The commercial products in the market are mainly fire fighting robots which are comparatively large and they cannot track automatically as they are manually operated. The proposed robot can run manually or automated mode and is used only for search/assist operation in a rescue mission.

C. Implementation of the Follow Hop Search Algorithm

The process flow diagram is shown in fig. 4 upon detection of fire, a trigger is generated by the camera system or fire alarm system or manually. It is wirelessly transmitted to the robot and/or control room. The controller of the robot is programmed to execute the following steps

- The controller continuously checks for trigger from the camera system / fire alarm system / manual trigger. Upon detection of trigger the robot starts to follow track 1.
- Check for obstacles along the path
  - i. If obstacle is not detected it follows the path till it reaches the destination.
  - ii. If an obstacle is detected then the robot checks for alternate path.
    - a. If alternate path is available, it automatically shifts to track 2. If the obstacle is large enough to block many numbers of tracks, then the robot tries to find the nth track that is not blocked.
    - b. If alternate path is not available the it scans the surroundings for 8 seconds and returns to the original location
- The process repeats till it reaches the destination.

An ultrasonic sensor is used to detect obstacles. Upon detection of an obstacle the robot automatically shifts itself to a nearby track. If the path is totally blocked and if there is no possibility to reach the destination, the robot rotates slowly for 360˚ three times so that the camera mounted captures/ live streams the whole area for 8 seconds and then turn back to the start point. With the help of Mobile module and a SIM card for network (as there would be no Wi-Fi in case of fire accident).

FHS algorithm

```
START

MOVE Forward

IF (Obstacle = "NO" && Junction= "YES") // if there is no
obstacle and Junction is present
 {
 CASE (TURN)
  {

   CASE1:  Left = "YES": TURN Left & CALL forward; //
if left path is found, turn left.

   CASE2:  Straight = "YES": GO Straight & CALL
forward; // if straight path is found, go straight.


   CASE3:  Right = "YES": TURN Right & CALL forward;
//if right path is found, turn right.

  }

 }

ELSE // if the track is interrupted with an obstacle

 {

  DO // this condition is executed if the track is interrupted
by an obstacle

  {

   BACKTRACK // Back track algorithm is fetched

  }

    WHILE (Junction == YES)

    {

     READ JUNCTION MEMORY
                                //memory from track is obtained
and optional track is opted from the junction

    }

   GO BACK TO IF // go back to if condition


REPEAT UNTILL (Memory condition is satisfied)

// Memory condition is set before the robot is operated

 i.e. Till the robot comes to initial condition or the starting
point
```

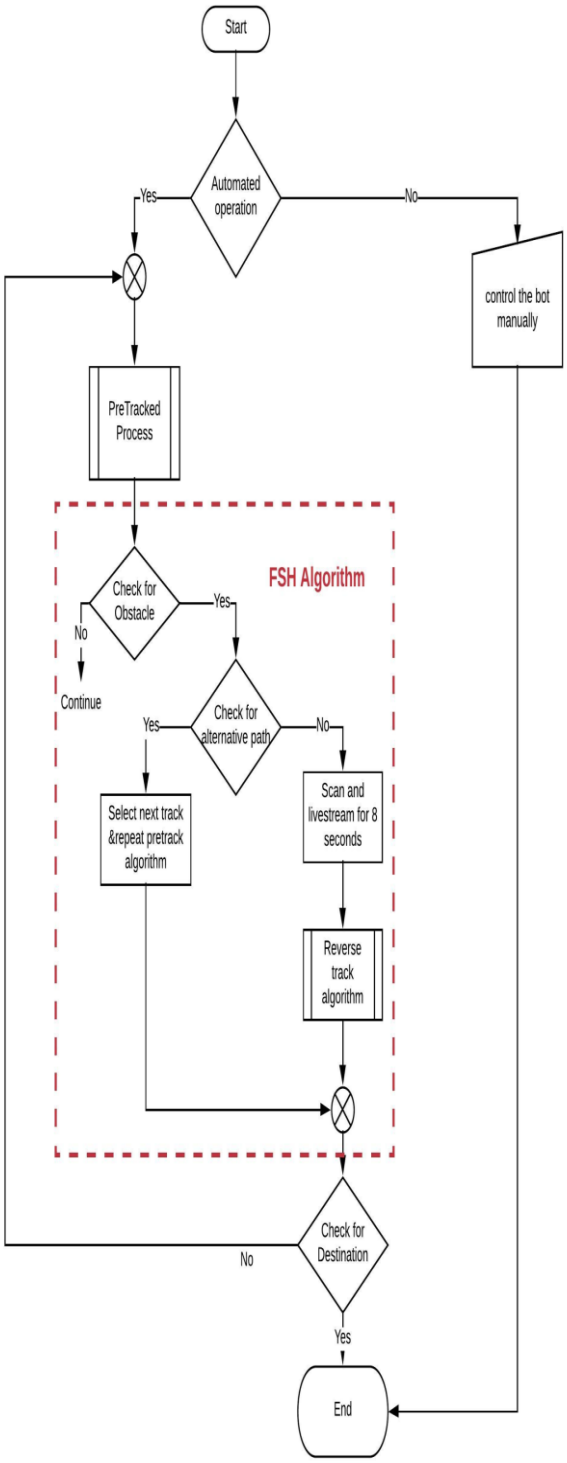

Fig.4 Flow diagram of proposed process

IV. RESULTS

A high speed robot was specifically designed to cover maximum distance in minimum time to assist the rescue operation during fire accidents. High speed motors and live streaming circuit elements are used to improve the efficiency of the rescue operation. The weight of the designed robot is 550 grams and it could be made lighter if required. The body weight and wheel size are reduced to increase the speed of the robot.

An example of a basic floor plan of a house with 3 tracks drawn on it is shown in fig.5. Tracks 1, 2 and 3 represented by the red, blue and violet lines represent the alternate tracks on the floor from the starting point and back to the same point. The primary track (red line) first searches the living room, then kitchen, closet, bathroom and bedroom. Then it searches the living room again before it returns to the starting point. The robot can be made to take more than one search till the arrival of the fire brigade as the humans may change their position depending on the intensity and spread of fire.

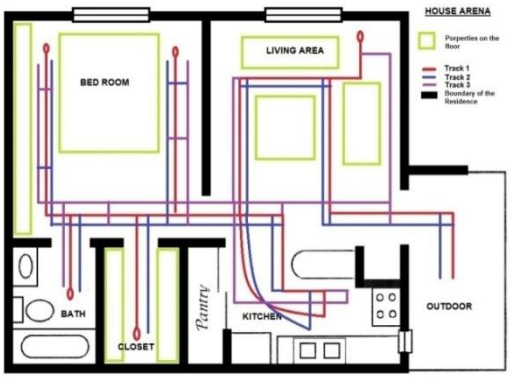

Fig. 5 Example of a Residence layout with tracks.

An example of a basic floor plan of an IT office with the implementation of track is shown in fig. 6.One or more optimal tracks must be selected based on the layout of the building, arrangement of furniture/assets in the building, number of occupants and probability of people in that location. If there is an overlap in tracks or the possible tracks are too close then the mobile robot will choose anyone of the track unless and until it faces an obstacle (refer table2 row 6). However the tracks are not inch perfect in the pre run of the robot. Various parameters that were considered during the design of the assist system and their effectiveness are listed below.

1. **Speed & Time**
   To test the speed of the robot and time taken to receive useful information we considered a residence with an area of 2400sq.ft, (refer fig 4). A number of test runs which included the best and worst case scenarios were done. The total track length from the starting point to the destination on an optimal track that facilitates maximum detection was approximately 460 feet or less. At an ideal speed (70%) the robot could cover the entire track and come back to the starting point in 89 seconds (minimum) to 115 seconds (maximum). A summary of the results and observations are listed below.
2. **Loops per residence/ plane**
   Ideally two or more loops would ensure safety for a larger area, as humans tend to move during evacuation and move from one place to another place of safety if they are stuck inside the building. The robot can be made to continuously monitor the building until destruction or manual

3. **Temperature consideration for wheels, body and wires**

   Wheels – Pololu wheels should be coated with a layer of silicon to make it fire resistant up to **120˚C** for 5 minutes

   Body – It can be used continuously in a temperature range of **105-120°C.** It begins to soften between **140-160°C** and starts to melt between **170-180°C.** Acrylic sheet can withstand temperatures down to **-28°C** without noticeable changes in properties.

4. **Visibility issues**

   The robot was tested in poor visibility conditions such as smoke, fog and watery environments that is typical for fire accident zones. The outcome of the tests is tabulated in table 2. Since the tracks are preprogrammed, the movement of the robot is not affected in such environments. However the quality of video streamed may be affected in poor lighting. To get ideal visibility on camera, a light is fixed to focus on the area of interest.

5. **Mobility Constraints**

   The robot was tested on various twists and turns on the floor (as listed in the Table 2). This is essential since the robot has to move inside a space were objects may be scattered due to the evacuation and dust/burnt items like wood, paper etc may necessitate the robot to choose alternate paths. The robot may be required to take a 90° perpendicular bend, acute & obtuse angle bend, semicircular curve to avoid obstacle or fine an alternate path. The robot was tested for these bends and the results are listed in table 2. Usually mobile robots face the main challenges in the area which has acute angle, perpendicular joints and deep curves, the mobile robot can overcome them with accurate tracing. The mobile robot has two values for speed, one is the base speed and other is the turn speed. The turn speed is calculated based on the smoothness of the floor; ideally the turn speed is 17 units less than the base speed.

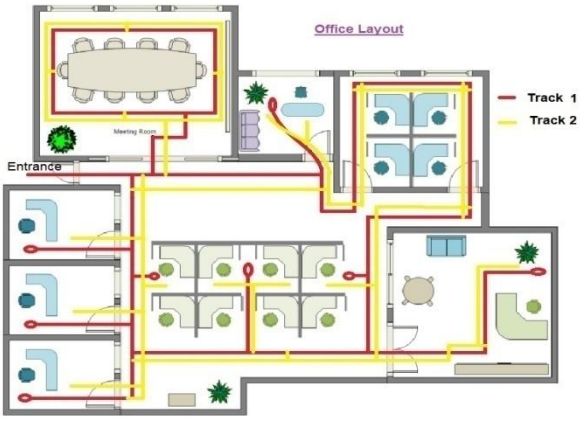

Fig. 6 Example of Office layout with tracks.

S. no	Parameters	Foggy Non visible opacity	Smoke With non-visible opacity	Watery – silicon coat on sensor
1.	90 degree perpendicular	✓	✓	✓
2.	Acute angle 30-89 degree	✓	✓	✓
3.	Obtuse angle 91-180 degree	✓	✓	✓
4.	T-joint	✓	✓	✓
5.	Loop angle 30 degree	✓	✓	✓
6.	Lines with gap & Marker line	✓	✓	✓

Table 2. Mobility constrains and visibility issues

Fig.7 View of the robot

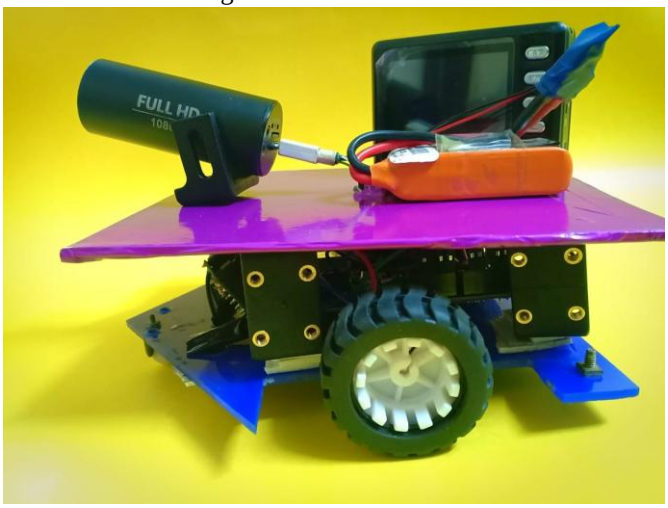

Fig.8 Side view of the robot

V. CONCLUSION

The proposed robot is programmed / trained only with the PSP once; its high accuracy output helps easy and early detection of human beings and ensures the protection of life. Since the location of the living being is found using FHS algorithm, the rescuers need not risk their life by searching the places where there are no humans/pets. An important element in the control and evacuation process is the speed and accuracy of the details of spread of fire and location of victims. Both these can be done using the proposed mobile robot.

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