Optimal Path Planning for Autonomous Mobile Delivery Robots

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Abstract— ***Obtaining the path from initial position to final position for the robot which should be hurdle free even though the whole vicinity is filled with obstacles should be the talk of the moment while working on finding the way for the robot. The whole idea behind this project is planning the paths for autonomous bots which are the future, while using multiple algorithms that will give us the ideal path in the most advantageous time so that the robot can move around in the cluttered space. To execute motion, the steps of an algorithm can be summed up in two lines. First it will scan the map or retrieve a stored map and second it will create a path accordingly. In order to achieve the ideal path as output, various methods are created, modifying the architecture of the algorithm present to develop an idealised algorithm for the applications of such delivery robots. Results and conclusion from the researches done till date, prove that algorithms are the key to generate and produce an optimal path for motion and it also proves that certain algorithms are suitable enough, to use them in real time. This report shares some light on and gives a perspective of the pros and cons of multiple path planning algorithms existing in present time.***

Keywords—optimal path, planning, mobile robots, A-star, Dijkstra, RRT, delivery robot, Breadth First Search, heuristic cost ,visibility graph, euclidian distance, obstacle avoidance.

I. Introduction

Path planning is a very popular field in the world of robotics and it plays a very vital role in traversing the mobile robots autonomously between node points [1]. It is the major aspect in the autonomous mobile robotics field. It enables to find an ideal pathway for the bots to traverse from an initial point to final point in a map space having hittable objects. In this process of motion planning, it is quite often that ideal path is needed to be ideal and optimal [2]. Navigation is process of creating a path or route that a mobile robot must perform to move without colliding with obstacles from one position to the other position by not following the wrong path. The 3 major concern for the navigation includes localization, robot motion control and optimal path planning [5]. Among these 3 areas, path planning to reach the goal is most vital area of concern. It helps in finalising the best pathway for the robot to transport within the map space [6].

Optimal path planning guides the mobile mobile vehicle or robot to trace an ideal path not getting into any of the obstacle space in the map. Optimal path planner should have the ability to eliminate the uncertain situations while searching in the uncertain map to reduce robot impact on the object and for finding the ideal path in lesser duration typically when path need to be altered regularly [4]. Representing the Robot in the C-Space (configuration space) and the implementing the algorithm are the two major points while path planning is considered and they are related to each other and have bigger to obtain the ideal path in minimal time [3].

In the following sections, the idea behind the different algorithms taken into consideration is briefly presented, and then the method in which they are implemented is discussed in detail. Consecutively, some simulation results are shown, and then the efficiency of each method is discussed based on the experimental results for these algorithms.

The description about each of the following sections described in this paper are discussed in the following. The Section II – Path planning algorithms gives a detailed information about the type of algorithm taken into consideration in this project and how each algorithm works. The Section III – Methods describes how each algorithm is implemented in this project to enable the movement of the robot starting from the very first node to the end node by staying away the obstacles and hindrances in the map. Advantages of each algorithm over the other is described in this section. The section gives the basic idea behind the background of this project. The computational advantage and complexity between the algorithm are also mentioned in this section. The Section IV discusses about the previous researches and findings in the sphere of autonomous mobile robots and planning. The ideas as well as the concepts inferred from the previous research papers are described in this paper. The complexity and practical issues seen in implementing these algorithms and general mathematical approach for implementing these algorithms are observed from these previous research papers and described under this section. The outcome of each of these researches are also briefly discussed. The Section V describes about the simulation of each of these algorithms in the obstacle cluttered environment or space. The simulation results from each of the algorithm and the path planning response from them in the obstacle space are mentioned here. The simulation output results with respect to each of the algorithm can be visualized in this section. The Section VI compares the response from each of these algorithms and shows the tabulation consisting of details of all the algorithms including their Time of execution, Number of explored nodes, and more. The better algorithm amongst all the compared algorithms for the functionality of the robot is described in this section. Section VII shows the analysis, Section VIII gives the conclusion we have reached from this research after analysing all the aspects. Section IX discusses the future scope for this approach.

The following assumptions are made in this project paper:

1. The obstacles are shape with nodes in set B. Let Vetex= B *U* [s,t] [10].
2. The robot is be observed as a point robot traversing among the obstacle space.
3. The obstacles move linearly with the constant speed.
4. The autonomous mobile robot has constant velocity and spontaneous deceleration and acceleration values.

II. PLAN OF ACTION

When it comes to the delivery robots apart from planning the path we need this process to happen in less time and this planned path should be an optimal path with less distance between its start and the goal point. Path planning methods noticed the complexity in computation. [6]. Basically, the short and ideal path between start and goal can be obtained through the Dijkstra algorithm, graph search, DFS algorithm, BFS algorithm, and A-Star algorithm and the other well-known algorithms including RRT, Depth First Search (DFS), RRT*, Visibility Graph and Weighted A-Star for delivery robot path planning application will be considered in this paper. From the comparison of the various factors including the algorithm with less time complexity, the one that gives the shortest path, and the one that is feasible based on the map the result will be summarized.

The list of algorithms taken for comparison of path planning for autonomous mobile robot are:

- A-Star
- Dijkstra
- RRT
- Weighted A*
- Breadth First Search (BFS)
- Depth First Search (DFS)
- RRT-Star (RRT*)
- Visibility Graph

The above-mentioned algorithms are compared based on the factors mentioned earlier and the optimal path planning algorithm is obtained.

III. METHODS

As mentioned above we are taking into consideration the above algorithms for finding an optimal path for our application and the methodology for implementing these algorithms are described below in detail,

1) Dijkstra Algorithm:

Dijkstra helps us calculate the shortest path between 2 points in the map. The steps we follow for Dijkstra algorithm are as follows:

- We initialize the distances according to the general notion.
- Then we start with the start point and calculate distances to the neighbour points.
- We then pick the next point with minimal distance and we repeat the distance calculation for the adjacent point.
- If a new minimal distance is found, we update the distance to the value.
- This is repeated till the goal point is found.

The above-mentioned steps are explained in the Pseudo code below.

Pseudocode:

```
Python

function Dijkstra(Graph, source):
       dist[source]  := 0                    // Distance from source to source is set to 0
       for each vertex v in Graph:            // Initializations
           if v ≠ source
               dist[v]  := infinity           // Unknown distance function from source to each
           add v to Q                         // All nodes initially in Q

      while Q is not empty:                  // The main loop
          v := vertex in Q with min dist[v]  // In the first run-through, this vertex is the s
          remove v from Q

          for each neighbor u of v:           // where neighbor u has not yet been removed fro
              alt := dist[v] + length(v, u)
              if alt < dist[u]:               // A shorter path to u has been found
                  dist[u]  := alt            // Update distance of u

      return dist[]
  end function
```

Figure 1: Dijkstra Pseudocode

Dijkstra steps [13]:

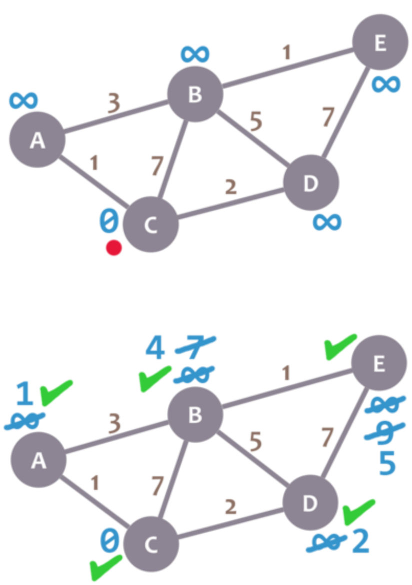


Figure 2: Dijkstra Steps

2) A-Star (A*) Algorithm:

This is the most widely used algorithm in finding short path application because of its efficiency.

What makes A-star different from other path planning algorithms is the formulae: f = g + h. The f,g,h get calculated every time a new node is created , where f represents the total cost, g is the distance b/w current point and initial point and H will be the heuristic distance (can be Manhattan or Euclidian) – estimated distance from the current point to the end point.
It is a modified version of Dijkstra, it avoids exploring the non-promising nodes using the heuristic distance to the goal node.

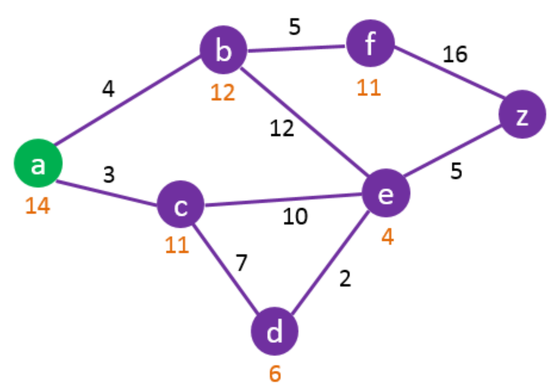
Pseudocode:

```
make an openlist containing only the starting node
make an empty closed list
while (the destination node has not been reached):
    consider the node with the lowest f score in the open list
    if (this node is our destination node) :
        we are finished
    if not:
        put the current node in the closed list and look at all of its neighbors
        for (each neighbor of the current node):
            if (neighbor has lower g value than current and is in the closed list) :
                replace the neighbor with the new, lower, g value
                current node is now the neighbor's parent
            else if (current g value is lower and this neighbor is in the open list ) :
                replace the neighbor with the new, lower, g value
                change the neighbor's parent to our current node

            else if this neighbor is not in both lists:
                add it to the open list and set its g
```

Figure 3: A Pseudocode*

A-Star Steps [13]:



Node	Status	Shortest Distance From A	Heuristic Distance to Z	Total Distance*	Previous Node
A	Visited	0	14	14	
B	Visited	4	12	16	A
C	Visited	3	11	14	A
D	Visited	10	6	16	C
E	Visited	12	4	16	D
F		9	11	20	B
Z	Current	17	0	17	E

* Total Distance = Shortest Distance from A + Heuristic Distance to Z

Figure 4: A Steps*

3) Weighted A*:

Weighted A* is a more modified version of A* algorithm. The formula mentioned above gets updated to f = g+εh . Weighted A* search trades off optimality for speed. Parameter ε biases the search towards the states that are closer to the foal state.

Pseudocode Weighted A*[Lecture – Session 6]:

```
FORWARD_SEARCH
  Q.Insert(x_I) and mark x_I as visited
  while Q not empty do
     x ← Q.GetFirst()
     if x ∈ X_G
        return SUCCESS
     forall u ∈ U(x)
        x' ← f(x, u)
        if x' not visited
           Mark x' as visited
           Q.Insert(x')
           parent(x') ⟵ x
           cost(x')=cost(x)+ l(x,u) + w * CostToGo (x')
        else
        if cost(x') > cost(x)+ l(x,u)
           UpdateCost(x') = cost(x)+ l(x,u) + w * CostToGo (
           parent(x') ⟵ x
           Resolve duplicate x'
  return FAILURE
```

Figure 5: Weighted A Pseudocode*

4) BFS (Breadth First Search):

BFS algorithm starts from the selected node and we explore the adjacent nodes which are directly joined to the parent node. We then explore the next level of adjacent nodes. We then move in a horizontal manner and visit all the nodes of the current layer.

Pseudocode:

```
BFS(v){
    {add v to queue and mark it}
    Add(Q, v)
    Mark v as visited
    while (not IsEmpty(Q)) do
    begin
        w = QueueFront(Q)
        Remove(Q)
        {loop invariant : there is a path from vertex w to every vertex in the queue Q}
        for each unvisited vertex u adjacent to w do
        begin
            Mark u as visited
            Add(Q , u)
        end { for }
    end{ while
```

Figure 6: BFS Pseudocode

BFS Node Exploration [15]

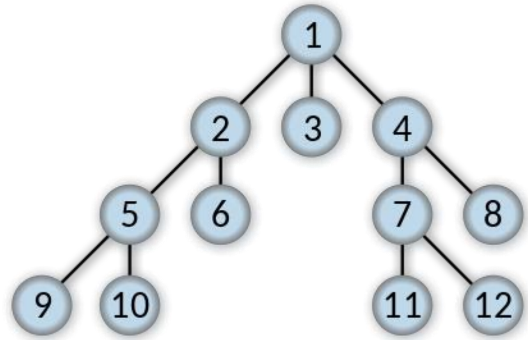


Figure 7: BFS Steps

5) Visibility Graph:

In Visibility Graph approach each node in the graph is a point location and each corresponding edge represents a visible bond in between them. The shortest path between two obstacles follows a straight line except at the vertices of the obstacle , where it may turn [12].

Pseudocode:

Algorithm 1 VISIBILITY GRAPH

1: **for all** vertex $v_n \in V, n = 1, 2, ...m$ **do**
2:     **if** v_i has the ability to see a vertex $v_j, v_i \neq v_j$ **then**
3:         add the (v_i, v_j) to E
4:     **end if**
5: **end for**
6: **return** g

Figure 8: Visibility Graph Pseudocode

Visibility Graph Exploration:

Figure 9: Visibility Graph Exploration

6) RRT Algorithm:

The premise of RRT is actually quite straight forward. Points are randomly generated and connected to the closest available node. Each time a vertex is created, a check must be made that the vertex lies outside of an obstacle. Furthermore, chaining the vertex to its closest neighbour must also avoid obstacles. The algorithm ends when a node is generated within the goal region, or a limit is hit [14].

Pseudocode:

```
RRT Pseudo Code

Qgoal //region that identifies success
Counter = 0 //keeps track of iterations
lim = n //number of iterations algorithm should run for
G(V,E) //Graph containing edges and vertices, initialize
While counter < lim:
    Xnew  = RandomPosition()
    if IsInObstacle(Xnew) == True:
        continue
    Xnearest = Nearest(G(V,E),Xnew) //find nearest verte
    Link = Chain(Xnew,Xnearest)
    G.append(Link)
    if Xnew in Qgoal:
        Return G
Return G
```

Figure 10: RRT Pseudocode

RRT Node exploration [14]:

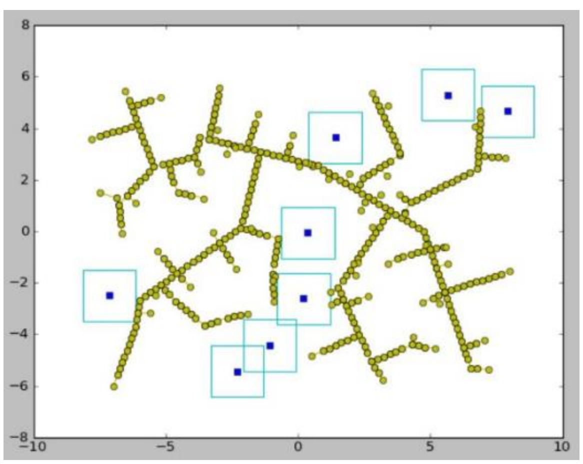


Figure 11: Dijkstra Node Exploration

7) RRT* (RRT-Star) Algorithm:

RRT* is an optimized version of RRT. RRT* records the distance each vertex has travelled relative to its parent vertex. This is referred to as the 'cost' of the vertex. After the closest node is found in the graph, a neighbourhood of vertices in a fixed radius from the new node are examined. If a node with a cheaper 'cost' than the proximal node is found, the cheaper node replaces the proximal node.
After a vertex has been connected to the cheapest neighbour, the neighbours are again examined. Neighbours are checked if being rewired to the newly added vertex will make their cost decrease. If the cost does indeed decrease, the neighbour is rewired to the newly added vertex [14].

Pseudocode:

```
RRT* Pseudo Code

Rad = r
G(V,E) //Graph containing edges and vertices
For itr in range(0…n)
    Xnew = RandomPosition()
    If Obstacle(Xnew) == True, try again
    Xnearest = Nearest(G(V,E),Xnew)
    Cost(Xnew) = Distance(Xnew,Xnearest)
    Xbest,Xneighbors = findNeighbors(G(V,E),Xnew,Rad)
    Link = Chain(Xnew,Xbest)
    For x’ in Xneighbors
        If Cost(Xnew) + Distance(Xnew,x’) < Cost(x’)
            Cost(x’) = Cost(Xnew)+Distance(Xnew,x’)
            Parent(x’) = Xnew
            G += {Xnew,x’}
    G += Link
Return G
```

Figure 12: RRT Pseudocode*

RRT* Node Exploration [14]:

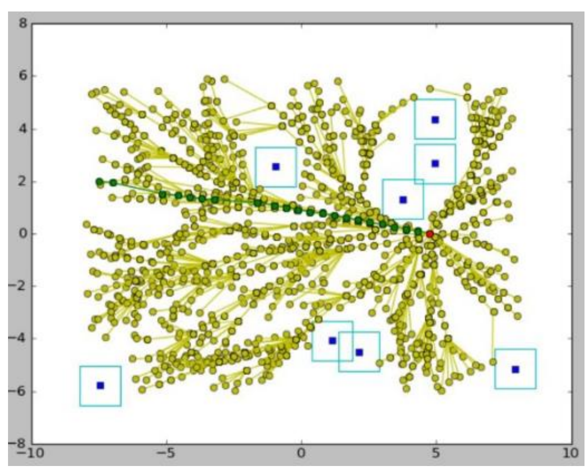


Figure 13: RRT Node Exploration*

The above-mentioned algorithms will be implemented* and they will be compared based on the simulation response. The factors which are taken into consideration for comparing these algorithms are Minimal Time, Shortest Path, Number of nodes created, Cost and feasibility.

Simulation Criteria for checking algorithms:

1. The Algorithm checked for one start point and one goal point with different radius of robot.
2. Also check for One start point and Multiple Goal points (Since for the delivery robot there will be multiple goal/delivery locations)
3. Check by varying the start and goal points
4. Check for farther goal node points

IV. PREVIOUS RESEARCH

There are wide range of researches that were carried out in the path planning algorithm and among which the researches which were carried out related to finding the time efficient algorithm, optimal path resulting algorithm, smoother path based algorithm, application based efficient algorithm and algorithm which is ideal for reaching the multiple goal points are observed for comparing the optimal path planning algorithm for delivery robots. Some of the research papers considered and gone through in doing this project and their drawbacks comparing to out initiative are mentioned below,

1) Previous researchers including, *Donald, Brooks and Kambhampti* [8,9] were working on a way to find a path with best duration by modifying a general method of plotting the workspace area with an efficient picturization of free space and obstacles and also use the best algorithm so as to look for and modify those data structures by using only the graph search algorithm and Dijkstra algorithm.

2) The research done by '*S. M. Masudur Rahman Al-Arif'* on the topic *"Comparative Study of Different Path Planning Algorithms: A Water based Rescue System"* compares the A*, Dijkstra and Graph Search algorithms for obtaining the optimal path and they are not considering the optimal time [11].

3) The research by '*Felipe Haro and Miguel Torres*' on the topic '*The Comparison of Path Planning Algorithms for Omni-Directional Robots in Dynamic Environments'* has results from the comparison of three path planning methods such as Bug Algorithm , Potential Field Algorithm and A* algorithm for omni-directional robots for finding ideal path and not taking consideration the other existing algorithms like Dijkstra [6].

4) The research by *'Emili Hernandes'* on the topic '*A comparison of homotopic path planning algorithms for robotic application'* compares algorithms RRT and A* for underwater navigation by autonomous vehicles.

5) '*Milena Karova'* done a research on the topic '*Path planning algorithms for an autonomous mobile robot'* comparing only the D* and A* path planning algorithms.

6) '*Pradeep Jayabala'* researched on '*Path planning of autonomous mobile robots: A survey and comparison'* comparing the Graph Search, Potential Field and Vector Field algorithm.

There are still more previous researches that we have analysed and not all are mentioned here.

There are still multiple algorithms that can be considered for searching and finding the optimal path between nodes and not all have been discussed and analysed in the previous researches. Previous researches came to a conclusion that the same task can be completed in a variation of time , space and effort while using different algorithms.

Each algorithm has its own speciality, pros and cons and for that reason our outputs are compared and discussed in detail in the fifth section of this report.

V. SIMULATION OUTPUTS

The Algorithms are executed and simulation results are obtained for different start and goal points for each algorithm.

Since the robot is considered for the parcel, food or mail delivery application, we have created an obstacle map for robot traversing as shown below depicting the real world environment.

Obstacle map:

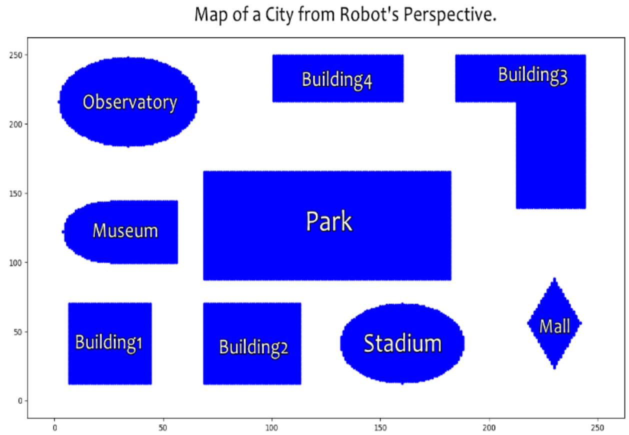


Figure 14: Obstacle map

The simulation results are shown below for all the algorithms with description.

1) BFS Simulation:

Points 1: Start Point (5,5) , Goal Point (249, 246)

Simulation Output

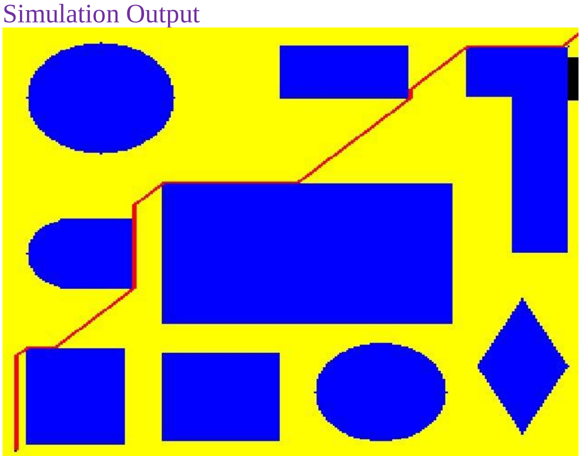


Figure 15: BFS Simulation

The Time for obtaining the path from BFS algorithm and path distance between the points considered can be seen in the python console as shown below in the image.

Output Console:

```
This BFS took 52.0972363948822 seconds
This BFS path length is 406.09040379562236 meters

Path Found
```

Figure 16: BFS Output Console

Points 2: Start Point (6,248) , Goal Point (239, 6)

Simulation Output

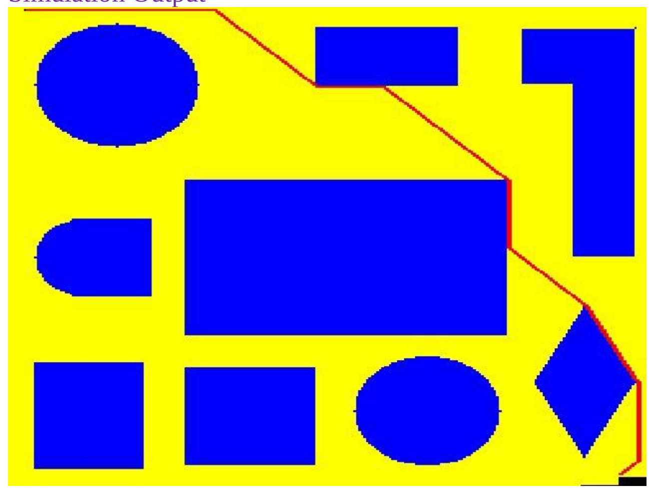


Figure 17: BFS Simulation

The Time for obtaining the path from BFS algorithm and path distance between the points considered can be seen in the python console as shown below in the image.

Output Console:

```
This BFS took 51.61190104484558 seconds
This BFS path length is 401.88939366884597 meters

Path Found
```

Figure 18: BFS Output Console

Points 3: Start Point (3,249), Goal Point (246,175)

Simulation Output

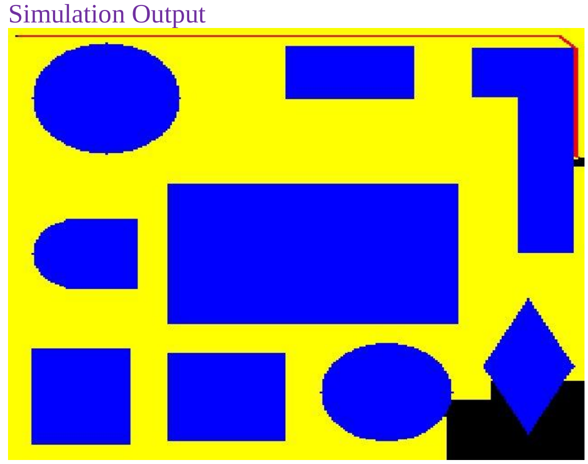


Figure 19: BFS Simulation

The Time for obtaining the path from BFS algorithm and path distance between the points considered can be seen in the python console as shown below in the image.

Output Console:

```
This BFS took 45.22405552864075 seconds
This BFS path length is 307.31370849898474 meters

Path Found
```

Figure 20: BFS Output Console

2) RRT Simulation:

Points 1: Start Point (5,5) , Goal Point (249, 246)

Simulation Output

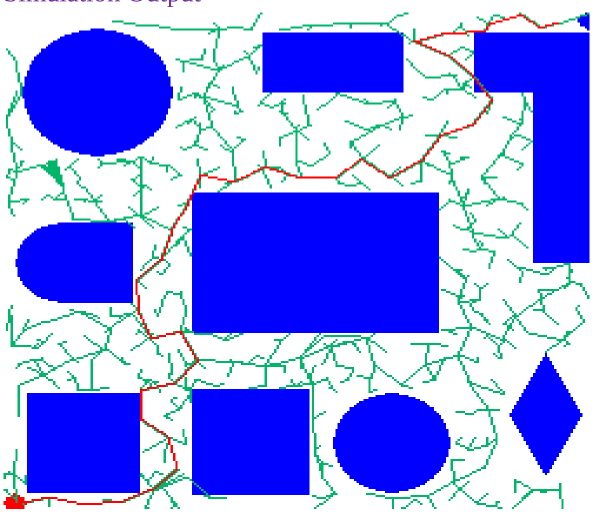


Figure 21: RRT Simulation

The Time for obtaining the path from RRT algorithm and path distance between the points considered can be seen in the python console as shown below in the image.

Output Console:

```
This RRT_Algorithm took 4.962814807891846 seconds
This RRT path length is 466.83728428149624 meters
```

Figure 22: RRT Output Console

Points 2: Start Point (6,248) , Goal Point (239, 6)

Simulation Output

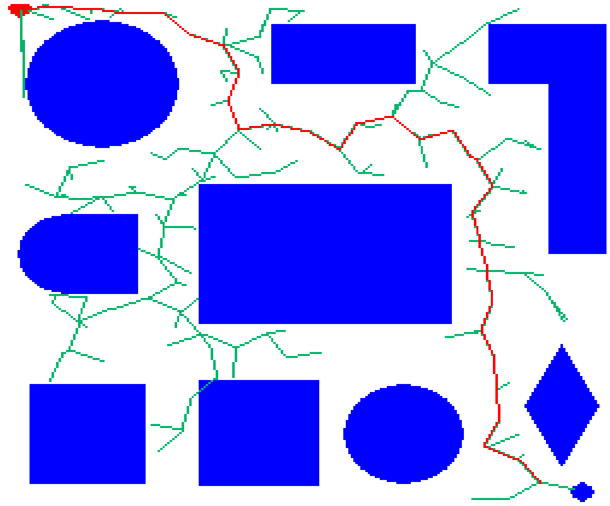


Figure 23: RRT Simulation

The Time for obtaining the path from RRT algorithm and path distance between the points considered can be seen in the python console as shown below in the image.

Output Console:

```
This RRT_Algorithm took 1.6127111911773682 seconds
This RRT path length is 498.11018981747924 meters
```

Figure 24: RRT Output Console

Points 3: Start Point (3,249), Goal Point (246,175)

Simulation Output

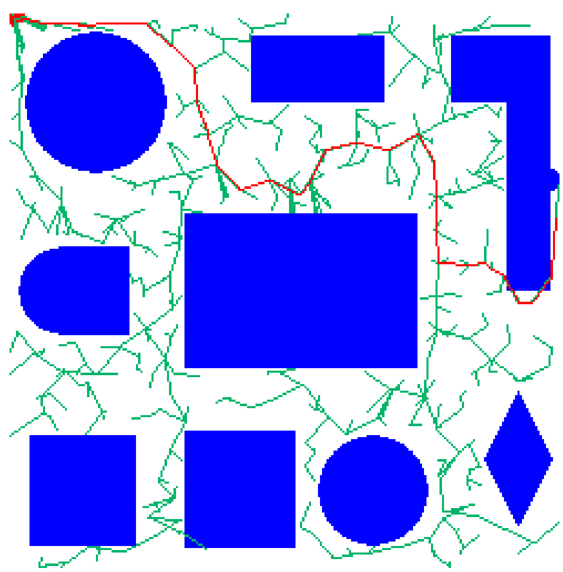


Figure 25: RRT Simulation

The Time for obtaining the path from RRT algorithm and path distance between the points considered can be seen in the python console as shown below in the image.

Output Console:

```
This RRT_Algorithm took 4.450629234313965 seconds
This RRT path length is 437.807403998078 meters
```

Figure 26: RRT Output Console

3) Dijkstra Simulation:

Points 1: Start Point (5,5) , Goal Point (249, 246)

Simulation Output

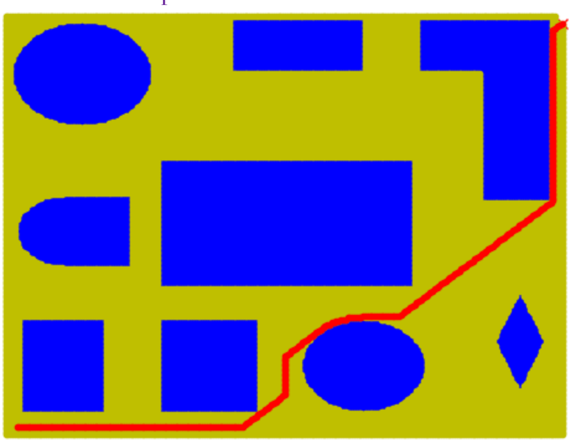


Figure 27: Dijkstra Simulation

The Time for obtaining the path from Dijkstra algorithm and path distance between the points considered can be seen in the python console as shown below in the image.

Output Console:

```
Make you selection:1
time ------> 6.713900089263916
Path Length ------> 417.04877323528007
```

Figure 28: Dijkstra Output Console

Points 2: Start Point (6,248) , Goal Point (239, 6)

Simulation Output

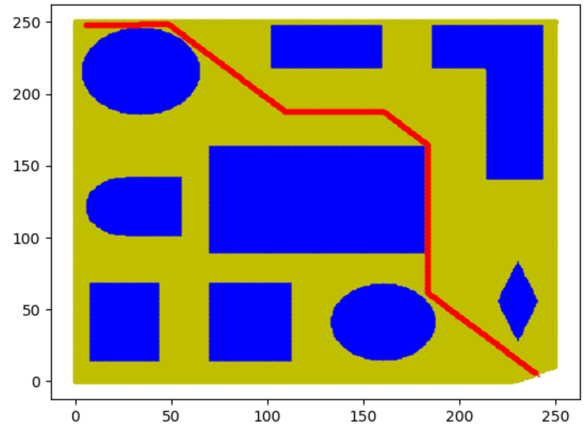


Figure 29: Dijkstra Simulation

The Time for obtaining the path from Dijkstra algorithm and path distance between the points considered can be seen in the python console as shown below in the image.

Output Console:

```
Make you selection:1
time ------> 6.667166233062744
Path Length ------> 394.40411229460733
```

Figure 30: Dijkstra Output Console

Points 3: Start Point (3,249) ,Goal Point (246, 175)

Simulation Output

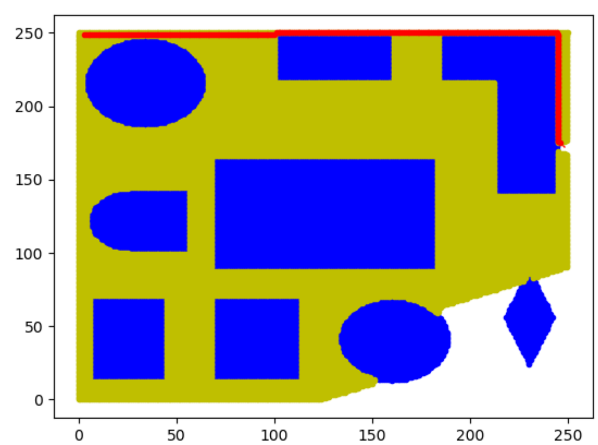


Figure 31: Dijkstra Simulation

The Time for obtaining the path from Dijkstra algorithm and path distance between the points considered can be seen in the python console as shown below in the image.

Output Console:

```
Make you selection:1
time ------> 5.826996088027954
Path Length ------> 317.2426406871193
```

Figure 32: Dijkstra Output Console

4) A-Star Algorithm:

Points 1: Start Point (5,5) , Goal Point (249, 246)

Simulation Output

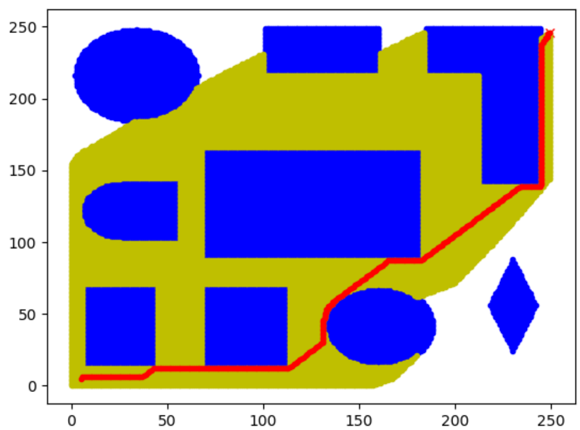


Figure 33: A-Star Simulation

The Time for obtaining the path from A-Star algorithm and path distance between the points considered can be seen in the python console as shown below in the image.

Output Console:

```
time ------> 8.167999267578125
Path Length ------> 417.048773235280
```

Figure 34: A-Star Output Console

Note: It looks like the node exploration is happening inside the obstacles in the above picture of A-Star simulation , but that is not true. The reason it looks like that in the above figure , is because of the way we are plotting it and also scaling. When we maximise or zoom the output GUI window we can see that the exploration is not inside the obstacle space. We have provided a zoomed image for your reference below

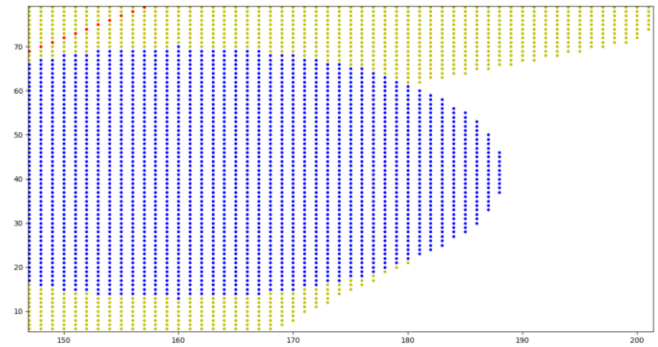


Figure 35: A-Star Magnified Simulation Response

The above figure is the magnified version of node exploration and it shows that nodes are not formed inside the obstacle space.

Points 2: Start Point (6,248) , Goal Point (239, 6)

Simulation Output

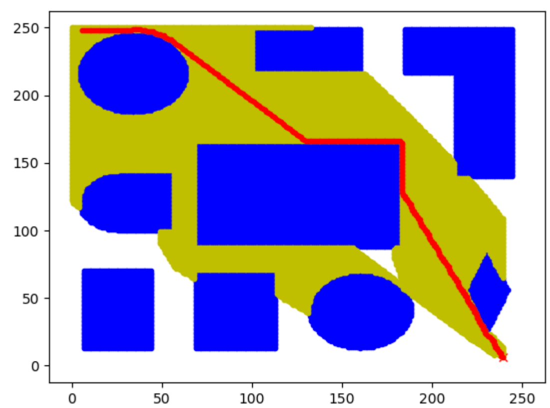


Figure 36: A-Star Simulation

The Time for obtaining the path from A-Star algorithm and path distance between the points considered can be seen in the python console as shown below in the image.

Output Console:

```
time ------> 6.38799786567688
Path Length ------> 394.40411229460733
```

Figure 37: A-Star Output Console

Points 3: Start Point (3,249) ,Goal Point (246, 175)

Simulation Output

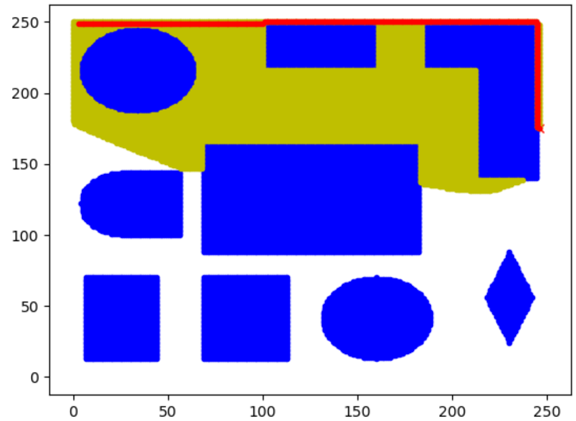


Figure 38: A-Star Simulation

The Time for obtaining the path from A-Star algorithm and path distance between the points considered can be seen in the python console as shown below in the image.

Output Console:

```
time ------> 3.7170205116271973
Path Length ------> 317.2426406871193
```

Figure 38: A-Star Output Console

5) RRT_Star (RRT*) Simulation:

Points 1: Start Point (65,60),Goal Point (225, 246)

Simulation Output

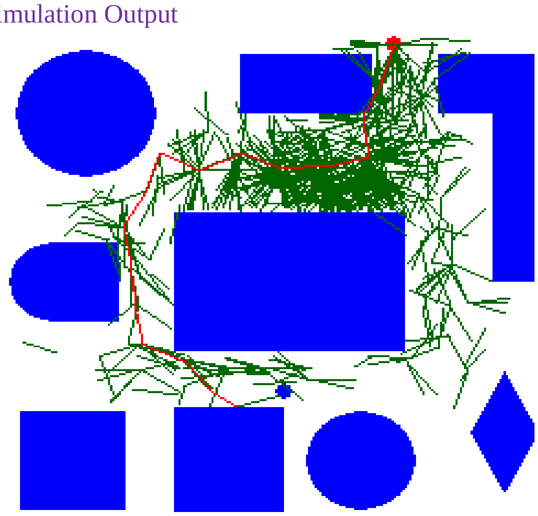


Figure 39: RRT Simulation*

The Time for obtaining the path from RRT* algorithm and path distance between the points considered can be seen in the python console as shown below in the image.

Output Console:

```
This RRT-Star(RRT*) took 11.984516143798828 seconds
This RRT-Star(RRT*) path length is 240.0 meters
```

Figure 40: RRT Steps*

Points 2: Start Point (6,248) , Goal Point (239, 6)

Simulation Output

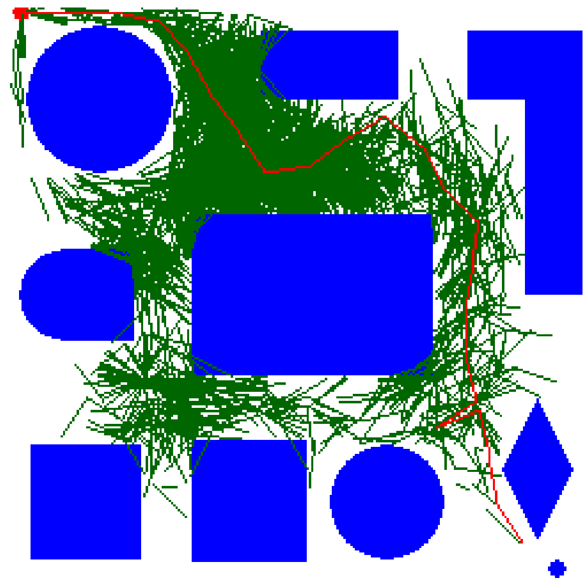


Figure 41: RRT Simulation*

The Time for obtaining the path from RRT* algorithm and path distance between the points considered can be seen in the python console as shown below in the image.

Output Console:

```
This RRT-Star(RRT*) took 12.786096572875977 seconds
This RRT-Star(RRT*) path length is 300.0 meters
```

Figure 42: RRT Output Console*

Points 3: Start Point (60,30) , Goal Point (230, 32)

Simulation Output

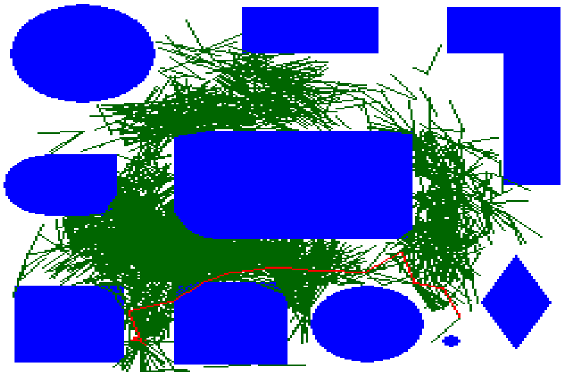


Figure 43: RRT Simulation*

The Time for obtaining the path from RRT* algorithm and path distance between the points considered can be seen in the python console as shown below in the image.

Output Console:

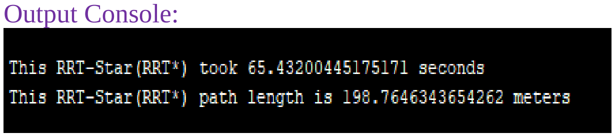


Figure 44: RRT Output Console*

6) Weighted A-Star Algorithm: (Weight =4)

In weighted A-star simulation even when the node exploration occurs, it is not visible in the output window as can be seen in the below figures. This happens since we are plotting 1000 nodes in a single iteration and since the nodes explored in case of 1st and 2nd points are less than 1000, the node exploration is not visible in the GUI.

Points 1: Start Point (5,5) , Goal Point (249, 246)

Simulation Output

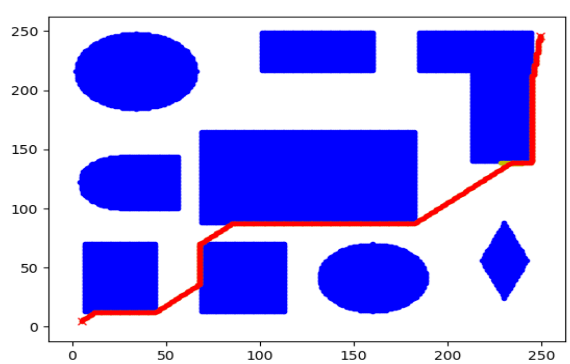


Figure 45: Weighted A Simulation*

The Time for obtaining the path from Weighted A-Star algorithm and path distance between the points considered can be seen in the python console as shown below in the image.

Output Console:

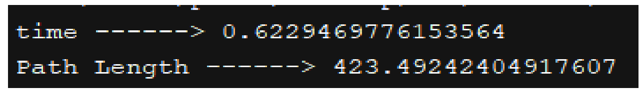


Figure 46: Weighted A Output Console*

Points 2: Start Point (6,248) , Goal Point (239, 6)

Simulation Output

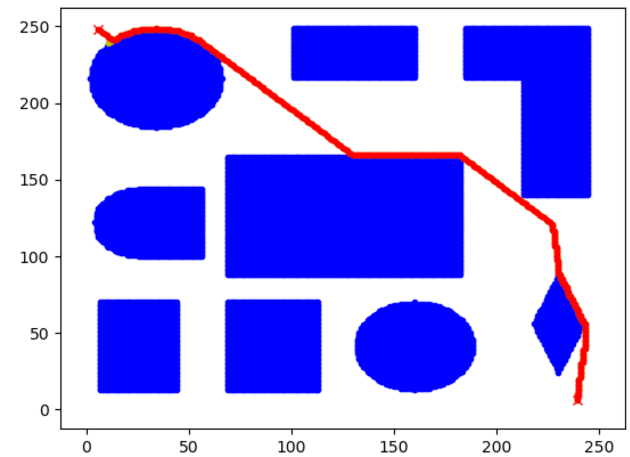


Figure 47: Weighted A Simulation*

The Time for obtaining the path from Weighted A-Star algorithm and path distance between the points considered can be seen in the python console as shown below in the image.

Output Console:

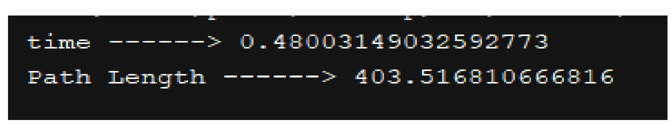


*Figure 48: Weighted A*Output Console*

Points 3: Start Point (3,249),Goal Point (246, 175)

Simulation Output

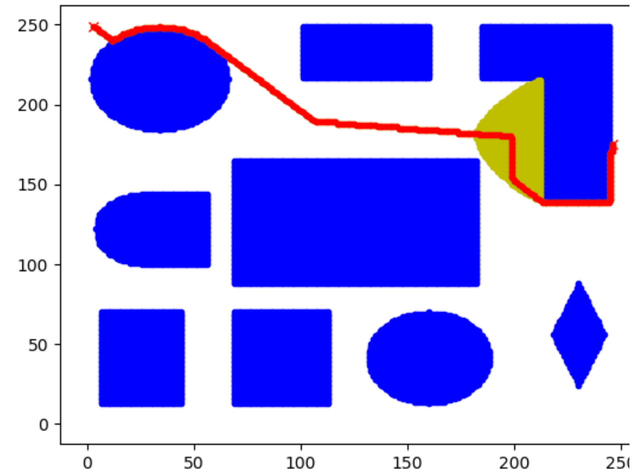


*Figure 49: Weighted A*Simulation*

The Time for obtaining the path from Weighted A-Star algorithm and path distance between the points considered can be seen in the python console as shown below in the image.

Output Console:

```
time ------> 1.0480244159698486
Path Length ------> 346.0782104868028
```

*Figure 50: Weighted A*Output Console*

7) Visibility Graph:

Points 1: Start Point (5,5) , Goal Point (249, 246)

Simulation Output

Figure with Visible Edges and Path

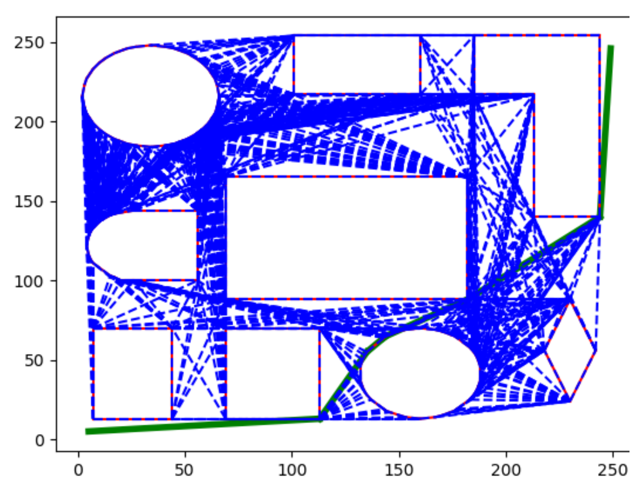


Figure 51: Visibility Graph Simulation

Figure with only Path

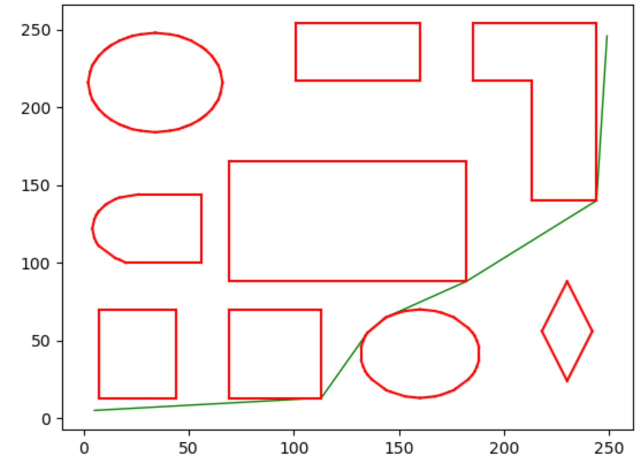


Figure 52: Visibility Graph Simulation

The Time for obtaining the path from Visibility Graph algorithm and path distance between the points considered can be seen in the python console as shown below in the image.

Output Console:

```
The time taken ---> 1.105395793914795
The length of the shortest path is 400.62081440265104
```

Figure 53: Visibility Graph Output Console

Points 2: Start Point (6,248) , Goal Point (239, 6)

Simulation Output

Figure with Visible Edges and Path

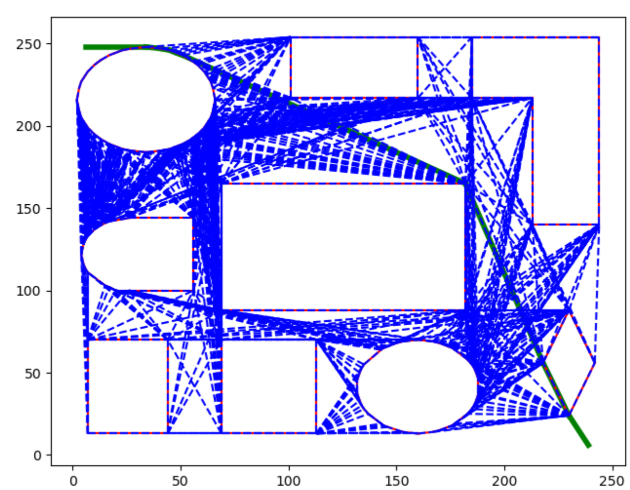


Figure 54: Visibility Graph Simulation

Figure with only Path

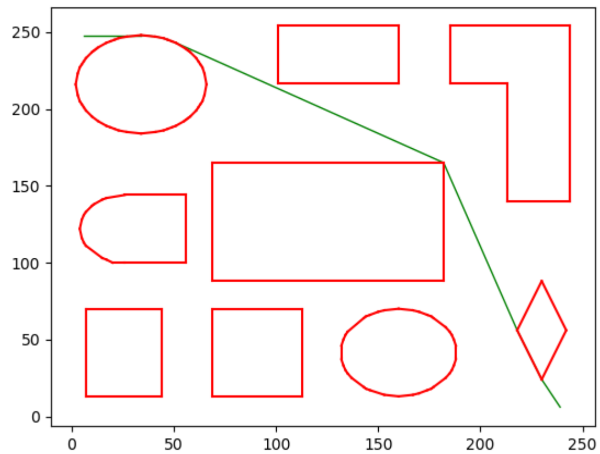


Figure 55: Visibility Graph Simulation

The Time for obtaining the path from Visibility Graph algorithm and path distance between the points considered can be seen in the python console as shown below in the image.

Output Console:

```
The time taken ---> 1.094254732131958
The length of the shortest path is 367.4572290797651
```

Figure 56: Visibility Graph Output Console

Points 3: Start Point (3,249),Goal Point (246, 175)

Simulation Output

Figure with Visible Edges and Path

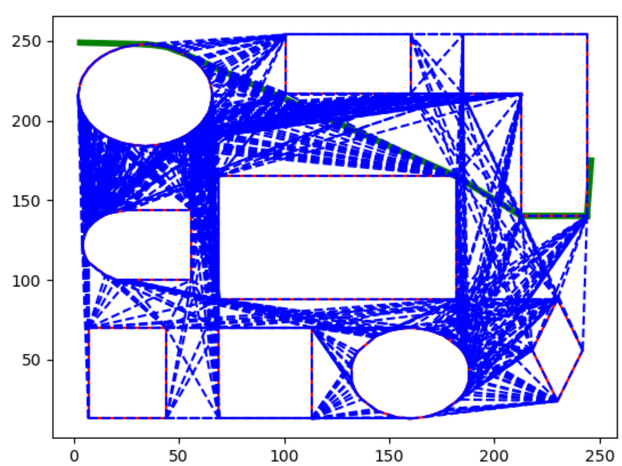


Figure 57: Visibility Graph Simulation

Figure with only Path

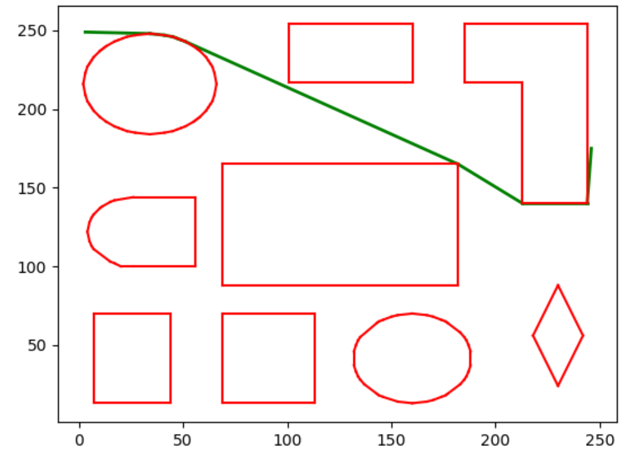


Figure 58: Visibility Graph Simulation

The Time for obtaining the path from Visibility Graph algorithm and path distance between the points considered can be seen in the python console as shown below in the image.

Output Console:

```
The time taken ---> 1.1003241539001465
The length of the shortest path is 307.26332429021346
```

Figure 59: Visibility Graph Output Console

VI. RESULT COMPARISION

1) BFS Algorithm Results:

The BFS algorithm is analyzed for 10 different initial and final nodes and the time for obtaining final path and the length(distance) of the final path in all the situations are obtained and tabulated as shown below.

The Algorithm is executed for some extreme start and goal points and some of the critical border points in the map and the following results are obtained.

Table 1: BFS Algorithm Result

Start Points	Goal Points	BFS_Path Time(sec)	BFS_Path Distance (m)
5,5	249,246	52.0972	406.0904
6,248	239,6	51.6119	401.8893

55,24	202,24	8.5002	157.1837
79,228	244,70	31.3172	252.8772
122,26	97,249	49.2647	276.2964
57,35	208,209	48.4822	288.267
241,20	6,157	49.1833	323.2497
246,213	64,120	29.6566	278.5512
3,249	246,175	45.224	307.3137
180,245	130,45	35.2217	250.8822

The above table shows the start point, goal point, Execution time of BFS logic, Final path length in each column for all the 10 different points taken into consideration.

2) RRT Algorithm Results:

The RRT algorithm is analyzed for 10 different start and goal points and the time to obtain the final path and the length(distance) of the final path in all the situations are obtained and tabulated as shown below.

The Algorithm is executed for some extreme start and goal points and some of the critical border points in the map and the following results are obtained.

Table 2: RRT Algorithm Result

Start Points	Goal Points	RRT Time taken(sec)	RRT Path Length (m)
5,5	249,246	2.3185	523.5177
6,248	239,6	1.6127	498.1101
55,24	202,24	3.9372	311.8312
79,228	244,70	2.2287	261.6156
122,26	97,249	7.08442	359.4895
57,35	208,209	1.5584	319.633
241,20	6,157	1.7822	359.5273
246,213	64,120	1.3407	348.6344
3,249	246,175	4.4506	437.8074
180,245	130,45	6.8887	295.7795

The above table shows the start point, goal point, Execution time of RRT logic, Final path length in each column for all the 10 different points taken into consideration.

3) Dijkstra Algorithm Results:

The Dijkstra algorithm is analyzed for 10 different start and goal points and the time to obtain the final path and the length(distance) of the final path in all the situations are obtained and tabulated as shown below.

The Algorithm is executed for some extreme start and goal points and some of the critical border points in the map and the following results are obtained.

Table 3: Dijkstra Algorithm Result

Start Points	Goal Points	Dijkstra Time taken(sec)	Dijkstra Path Length (m)
5,5	249,246	9.3425	417.048
6,248	239,6	7.4542	394.404
55,24	202,24	2.49186	156.941
79,228	244,70	6.1353	250.3624
122,26	97,249	7.6209	273.7817
57,35	208,209	7.547532	292.78174
241,20	6,157	7.167	318.107
246,213	64,120	6.2906	300.9655
3,249	246,175	6.38497	317.2426
180,245	130,45	5.13572	233.1543

The above table shows the start point, goal point, Execution time of Dijkstra logic, Final path length in each column for all the 10 different points taken into consideration

4) A* Algorithm Results:

The A* algorithm is analyzed for 10 different start and goal points and the time to obtain the final path and the length(distance) of the final path in all the situations are obtained and tabulated as shown below.

The Algorithm is executed for some extreme start and goal points and some of the critical border points in the map and the following results are obtained.

Table 4: A Algorithm Result*

Start Points	Goal Points	A* Time taken(sec)	A* Path Length (m)
5,5	249,246	8.2039	417.048
6,248	239,6	6.606	394.404
55,24	202,24	0.648	156.941
79,228	244,70	2.88	250.3624
122,26	97,249	2.2592	273.7817
57,35	208,209	4.8385	292.7817
241,20	6,157	4.2052	318.107
246,213	64,120	4.4206	300.9655
3,249	246,175	3.8827	317.2426
180,245	130,45	2.26	233.1543

The above table shows the start point, goal point, Execution time of A-Star logic, Final path length in each column for all the 10 different points taken into consideration

5) RRT-Star (RRT*) Algorithm Results:

The RRT-Star algorithm is analyzed for 10 different start and goal points and the time to obtain the final path and the length(distance) of the final path in all the situations are obtained and tabulated as shown below.

The Algorithm is executed for some extreme start and goal points and some of the critical border points in the map and the following results are obtained.

Table 5: RRT Algorithm Result*

Start Points	Goal Points	RRT* Time taken(sec)	RRT* Path Length (m)
5,5	249,246	11.98450	240
6,248	239,6	21.34680	312.1187
55,24	202,24	65.28170	198.9813
79,228	244,70	43.13450	291.1924
122,26	97,249	32.23440	413.1442
57,35	208,209	12.23440	183.2495
241,20	6,157	26.14340	427.1334
246,213	64,120	11.98420	353.754
3,249	246,175	93.24130	493.1244
180,245	130,45	66.34250	386.2342

The above table shows the start point, goal point, Execution time of RRT-Star logic, Final path length in each column for all the 10 different points taken into consideration

6) Weighted A-Star (Weighted A*) Algorithm Results:

The Weighted A-Star algorithm is analyzed for 10 different start and goal points and the time to obtain the final path and the length(distance) of the final path in all the situations are obtained and tabulated as shown below.

The Algorithm is executed for some extreme start and goal points and some of the critical border points in the map and the following results are obtained.

Table 6: Weighted A Algorithm Result*

Start Points	Goal Points	Weighted A* Time taken(sec)	Weighted A* Path Length (m)
5,5	249,246	0.5	423.4924
6,248	239,6	0.444	403.5168
55,24	202,24	0.184	167.7696
79,228	244,70	0.268	250.3624
122,26	97,249	0.484	283.1543
57,35	208,209	0.26231	293.3675
241,20	6,157	0.27524	321.4213
246,213	64,120	0.5988	324.9411
3,249	246,175	0.782	346.0782
180,245	130,45	0.54611	273.5218

The above table shows the start point, goal point, Execution time of Weighted A-Star logic, Final path length in each column for all the 10 different points taken into consideration.

7) Visibility Graph Algorithm Results:

The Visibility Graph algorithm is analyzed for 10 different start and goal points and the time to obtain the final path and the length(distance) of the final path in all the situations are obtained and tabulated as shown below.

The Algorithm is executed for some extreme start and goal points and some of the critical border points in the map and the following results are obtained.

Table 7: Visibility Graph Algorithm Result

Start Points	Goal Points	Visibility Graph Time taken(sec)	Visibility Graph Path Length (m)
5,5	249,246	1.09773	400.6208
6,248	239,6	1.41290	367.45722
55,24	202,24	1.45944	152.2761
79,228	244,70	1.45736	234.181
122,26	97,249	1.38380	257.9942
57,35	208,209	1.46100	275.1865
241,20	6,157	1.48003	298.3527
246,213	64,120	1.45323	294.789
3,249	246,175	1.08740	307.2633
180,245	130,45	1.47067	226.079

The above table shows the start point, goal point, Execution time of Visibility Graph logic, Final path length in each column for all the 10 different points taken into consideration

Thus based on the simulation response from all the algorithms, the simulation time and the final path length are obtained and these results are used for comparing the optimal algorithm for the delivery robots in the real world environment.

VII. ANALYSIS OF ALGORITHMS

The algorithms are executed, and their execution duration, output path and their length are obtained. The average time of execution for any point within the map for algorithm is mentioned below,

Table 8: Algorithm and Avg Execution Time

Algorithm	Average Execution Time (sec)
Dijkstra	6.5570
A-Star	4.0204
RRT	2.3185
Weighted A*	0.4334
RRT-Star	38.3297
Visibility Graph	1.3763
BFS	40.0559

On considering the average time of execution of each algorithm, we can observe that the Weighted A* Algorithm executes in minimal time for any point or node in the map. But we cannot come to conclusion that this is the optimal algorithm because of certain factors, of how far are goal points from the start points or even though it took less time, did it travel less distance compared to others and hence we are considering other factors for comparison of the algorithms.

It is observed from the simulation results that the RRT and RRT* methods can find the goal node in the known environment, but both methods explore the nodes in very random manner as the name suggests. The nodes explored between the start and goal in one iteration may not be the same in other iteration. So, the time to reach the goal node is very random in both the cases, sometimes it takes less time and in other iteration it may take more time to reach the goal and hence we cannot rely on this algorithm for finding the goal path considering the optimal path and time for the delivery robots.

Also, when the visibility graph is taken into consideration, the map and obstacle points should be well defined prior to the execution of algorithm in order to form the vertex joining the corner points and edges in the obstacle space. For an autonomous robot moving in the real world, the obstacle it faces is not static and it is more dynamic and hence it is not possible to predefine the map. The obstacle location keeps varying and hence it is not possible to predefine the obstacle space for the execution of the Visibility Graph algorithm execution. It is also more difficult to convert all the obstacles into a shape and then match all the vertices. The path taken in consideration in a visibility graph is always a straight line and it takes sharp turns at the corners of the obstacle, which is not feasible in real life. Hence this algorithm is not reliable for path planning to navigate robot in space avoiding the obstacles. Thus, the other four algorithms are taken into consideration for obtaining the optimal path for robot navigation.

The execution time varies based on the location of the start and goal node points. Based on the simulation results, we observe that there are three extreme points in the map. Comparing the execution time and path length of the algorithms for the three extreme points below

Case1: Start [5,5] , Goal [249, 246]

Table 9: Case-1_Algorithm Comparison

Algorithm	Execution Time (sec)	Path Length (m)
BFS	52.0972	406.0904
A-Star	8.2039	417.048
Weighted A*	0.5000	423.4924
Dijkstra	9.3425	417.048

The above tabulation shows the execution time and path length for the four algorithms that can be used for delivery robots.
On comparing the execution time, we can observe that the Weighted A* algorithm is more optimal as it has the lowest execution time of 0.5seconds than all the other methods.
But when the path distance is considered the BFS algorithm seems to be optimal since it forms a path with minimal length of 406meters.

Case2: Start [6,248] , Goal [239, 6]

Table 10: Case-2_Algorithm Comparison

Algorithm	Execution Time (sec)	Path Length (m)
BFS	51.6119	401.8893
A-Star	6.606	394.404
Weighted A*	0.444	403.5168
Dijkstra	7.4542	394.404

The above tabulation shows the execution time and path length for the four algorithms that can be used for delivery robots.
On comparing the execution time, we can observe that the Weighted A* algorithm is more optimal as it has the lowest execution time of 0.444seconds than all the other methods.
But when the path distance is considered the A* and Dijkstra algorithm seems to be optimal since it forms a path with minimal length of 394.404meters.

Case3: Start [3,249] , Goal [246,175]

Table 11: Case-3_Algorithm Comparison

Algorithm	Execution Time (sec)	Path Length (m)
BFS	45.224	307.3137
A-Star	3.8827	317.2426
Weighted A*	0.782	346.0782
Dijkstra	6.38497	317.2426

The above tabulation shows the execution time and path length for the four algorithms that can be used for delivery robots.
On comparing the execution time we can observe that the Weighted A* algorithm is more optimal as it has the lowest execution time of 0.782seconds than all the other methods.
But when the path distance is considered the BFS algorithm seems to be optimal since it forms a path with minimal length of 307.3137meters.

VIII. CONCLUSION

This project paper describes seven path planning method or algorithms for a robot navigation from start and goal point in the map with obstacles. Based on the simulation experiment results and the strategic inference from the seven algorithms few conclusions can be derived for the obstacle map with static obstacles.

The comparison of the simulation results showed that if the execution time is primary criteria for selection of the algorithm, then the Weighted A* algorithm is comparatively more optimal than the others when the obstacles in the map are static and when the

environment in which the robot navigate is well known with one start and goal point.
The A-star is second best method when the execution time is considered. In weighted A* method, the heuristic function and the weight should be selected carefully to obtain the path that is shorter and has lower cost. The weighted A* method does not guarantee a path that is shortest. Weighted A* compromises on the optimality of the path for speed.

But when there is one start point and multiple goal points the BFS algorithm may be better choice if the execution time is considered. Also, since the Dijkstra method is not involving the heuristic cost in its algorithm, it explores more nodes and these explored nodes will be an advantage when there are multiple goal points.

When the simulation results for all the algorithm taken into consideration are obtained, they were analyzed and compared based on the time and distance.

We concluded that, if execution time of the algorithm is our only our sole criteria for deciding, we will always go for weighted A-star.
If we need to consider only the path length, we have two options, Dijkstra and A-star, but we need to consider both time and length of the path, we will choose A-star, because it gives the optimal path in less amount of time.

Since, our application was Delivery Robots, we can go with A-star.
In a more general scenario, we must decide a tradeoff between which factor is more important for our application, is it time or is it path length. Depending on the requirement by the application, we can finalize an algorithm.

IX. FUTURE WORK

1) This study can be extended for one start point and multiple goal points.
2) More algorithms can be compared with the existing ones.
3) Certain algorithms can be combined with parameters such as heuristic costs, to make existing algorithms more robust.
4) In future we can consider for dynamic obstacles and uncertainties for better analysis.
5) In Weighted A* and A* the Euclidean method is used in heuristic function and it can be checked with the other method and it may yield a better result.

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