Drone Delivery Systems Using Graph Theory

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***Abstract*—The objective of this project is to implement the last mile delivery systems using drones implementing graph theory concepts. The system consists of multiple warehouses and customers located in a geographical region, and a fleet of drones that can transport packages from warehouses to customers. Graph Theory concepts are used to model the system as a graph, where nodes represent warehouses and customers and edges represent the flight paths of drones between them. We are also assuming that there are charging points to decrease the number of drones required to complete multiple packages delivery without reaching the warehouse for charging. The system employs various algorithms such as Dijkstra's algorithm and all pair shortest path algorithm to compute the shortest and fastest routes.**

Keywords—drones, last mile delivery system, graph theory

I. Introduction

The last mile delivery of goods and packages is a critical component of many online shopping sites. Traditional delivery methods can be inefficient and expensive, often resulting in delays and increasing costs. In recent years, drones are increasingly used for last mile deliveries to decrease the fuel costs and combat the worker shortage.

Drones became popular as a last mile delivery option due to their low operating costs and speed of delivery. However, drones efficient and effective usage requires intelligent systems to be used for optimizing delivery routes, manage multiple packages and handle battery life and charging issues. The system also considers drone payload capacity and battery life to determine the optimal delivery sequence. The inclusion of charging points and the ability for a single drone to carry multiple packages also enhances the efficiency and effectiveness of the delivery system.

II. Graph Theory Concepts

Here, we are going to briefly discuss the concepts of Graph Theory that are required to solve the delivery system.

Weighted Graphs: The delivery network is represented as a weighted graph, where nodes represent delivery locations, and edges represent the distance between locations.

Shortest Path Algorithms: To determine the most efficient delivery route, shortest path algorithms such as Dijkstra's algorithm or Open Traveling Salesman Problem algorithm can be used. These algorithms compute the shortest path between two nodes in a weighted graph, considering the weight of each edge.

Directed Graphs: A directed graph can be used to represent the delivery sequence, where nodes represent delivery locations, and edges represent the order in which the packages need to be delivered.

Capacitated Vehicles Routing Problem (CVRP): CVRP is a combinatorial optimization problem that involves finding the most efficient way to deliver packages using a limited number of vehicles with limited carrying capacity. This concept is essential for determining the optimal delivery sequence for a drone with limited payload capacity.

Charging Points as Nodes: The use of charging points in the delivery network can be represented as additional nodes in the graph, where drones can recharge their batteries. The location and capacity of these nodes can be optimized to minimize the number of charging stops required.

By applying these graph theory concepts, the proposed last mile drone delivery system can efficiently and effectively optimize delivery routes, manage multiple packages, and handle battery life and charging issues.

III. Flow in Delivery System Scenarios

There are several scenarios that the last mile delivery system can be used can include for. Here are some scenarios:

A. Single Package Delivery

Suppose there is a package that needs to be delivered from warehouse to a customer. The delivery network is represented as a weighted graph, where nodes represent delivery locations, and edges represent the distance between locations.

The algorithm starts by identifying the shortest path between warehouse and the customer using Dijkstra's algorithm. This algorithm computes the shortest path between two nodes in a weighted graph, considering the weight of each edge. Once the shortest path is identified, the algorithm determines the optimal delivery sequence. In this case, there is only one package, so the directed graph will only have two nodes - warehouse and customer.

The algorithm then checks the payload capacity and battery life of the drone to determine if the package can be delivered in one go. If the payload capacity or battery life is insufficient, the algorithm will add charging points to the graph, where the drone can recharge its battery. The location and capacity of these nodes can be optimized to minimize the number of charging stops required. Once the optimal delivery sequence is determined, the drone takes off from warehouse and follows the directed graph to deliver the package to customer.

Overall, this scenario shows how the proposed last mile drone delivery system can efficiently and effectively deliver a single package using graph theory algorithms to optimize delivery routes and manage battery life and charging issues.

B. Multiple Package Delivery

Suppose there are multiple packages that need to be delivered from point A, with delivery locations at points B, C, D, E, F, and G. The delivery network is represented as a weighted graph, where nodes represent delivery locations, and edges represent the distance between locations. To have a safe distance we assume that drone has a 5 miles power backup. This helps in mitigating low battery situations and reach charging points, if a charging point lies within 5miles radius of the delivery location.

The algorithm starts by identifying the route using the Open Traveling Salesman Problem (asymmetric TSP). This algorithm computes the shortest path between all pairs of nodes in a weighted graph.

Once the shortest path is identified, the algorithm determines the optimal delivery sequence for the packages. This is done by creating a directed graph, where nodes represent delivery locations, and edges represent the order in which the packages need to be delivered. The algorithm considers the payload capacity and battery life of the drone to determine the optimal delivery sequence for the packages.

We take the sequence and the distance that can be travelled by drone, in each iteration we decrease the travelable distance of drone by the distance already travelled. If the upcoming delivery distance and the shortest charging point from it is less than the distance travelable by drone, then we can continue to next iteration, else we add a charging point to the sequence between current and next delivery location.

Once the overall sequence of locations along with charging points is determined, we can start the delivery.

ALGORITHM

Multiple Package Delivery:

1. Use the Open Traveling Salesman Problem (asymmetric TSP) algorithm to compute the shortest path between all pairs of nodes in the weighted graph.
2. From the TSP solution, determine the optimal delivery sequence for the packages. Create a directed graph, where nodes represent delivery locations and edges represent the order in which the packages need to be delivered.

   $L(S,j) = \min L(S-\{j\}, i)+d(i,j)$ where $i \in S$, $i \neq j$,

   $S \in \{C1, C2, C3, \ldots, Cn\}$ and $L(S, j)$ represents the shortest distance required to traverse all the nodes in the set S exactly once, starting from node 1 and concluding at node j.
3. For each delivery location in the sequence, compute the shortest distance to the nearest charging point.
4. Initialize the drone's travelable distance to its maximum range and start at the first delivery location in the sequence.
5. In each iteration, subtract the distance already travelled from the drone's travelable distance, and check if the upcoming delivery location is within the remaining distance.
6. If the upcoming delivery location is within the remaining distance, continue to the next iteration.
7. If the upcoming delivery location is beyond the remaining distance, add a charging point to the sequence between the current and next delivery location. The charging point should be the nearest point to the next delivery location that is within the drone's remaining travelable distance.
8. Update the drone's travelable distance to its maximum range and continue to the next iteration.
9. Repeat steps 6-9 until all delivery locations have been visited.
10. Once all packages have been delivered, return to the nearest charging point or warehouse.

EVALUATION

We assume warehouses, customers as vertices and edges as the path between them and weights of the edges as distance between the two vertices. First, we convert the given graph into adjacency matrix.

	W	$C1$	$C2$	$C3$	$C4$
W	0	12	10	19	8
$C1$	12	0	3	7	2
$C2$	10	3	0	6	20
$C3$	19	7	6	0	4
$C4$	8	2	20	4	0

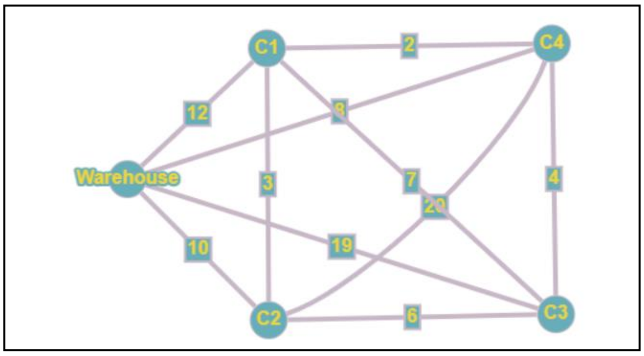

Fig 1: Warehouses and package delivery locations converted to graph along with the distances.

Using Open Traveling Salesman Problem algorithm, we get

$$W \rightarrow C2 \rightarrow C1 \rightarrow C4 \rightarrow C3$$

10 3 2 4

Now we assume that the drone has a maximum capacity to fly 18 miles and 5 miles backup power. After reaching C2 we have charging left for another 8 miles. So, we proceed to C1 that has a cost of 3 miles. After reaching C1 we have a charge for 5 miles. So, we proceed to C4 that has 2miles.

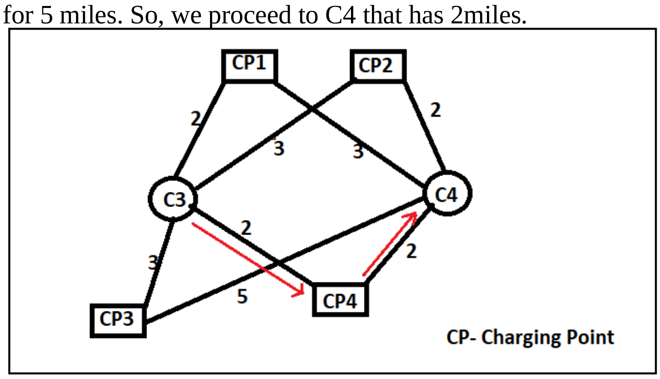

Fig 2: Finding the shortest path between delivery points via charging points.

The charge at C4 is 3 miles. To reach C3 we need a capacity of 4 miles, but we are left with only 3miles. So now we will search for the nearest charging point and add it to the delivery sequence.

Now we use the charging points that are within the 5 miles radius of both C3 and C4 to achieve the shortest path between C3 and C4 through the selected charging point. So, we calculate path from C3 to C4 via all available the charging points and select the shortest path i.e., C3 → CP4 → C4 with distance of 4miles.

After reaching CP4 and recharging we get the maximum capacity back to 18 miles along with 5 miles buffer backup power. Now we can proceed with C4 delivery.

RISKS

1. Inaccurate data: The algorithms rely on accurate data to make decisions, so any inaccuracies or errors in the data could lead to incorrect decisions, such as selecting the wrong delivery route or destination.

2. Limited scope: Algorithms used in drone delivery systems may have limited scope or be unable to account for unexpected or unusual situations, such as bad weather or restricted air spaces.

3. Training: The development and application of algorithms in drone delivery systems require specialized training and expertise, which could be a barrier to adoption or lead to a shortage of qualified personnel.

4. Operational limitations: The use of algorithms in drone delivery systems may be limited by factors such as battery life, range, or payload capacity, which could impact the system's overall effectiveness and efficiency.

5. Regulatory compliance: The use of algorithms in drone delivery systems could potentially violate regulations or laws, especially around airspace regulations. This could result in legal penalties or damage to the reputation of the company involved.

FUTURE SCOPE

1. Charging points can be used as small warehouses to pick packages if the drone has capacity.
2. Development of code in Python to simulate the drone delivery system.
3. Adding delivery windows selected by the customers to the system to calculate the efficient path.
4. After completing the delivery sequence, we can route the drone to nearest warehouse if the charge is available or we can visit a charging point to continue to the warehouse.

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