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T1 ________________	**1926080**	F1 ________________
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T3 ________________	Problem Chosen	F3 ________________
T4 ________________	**B**	F4 ________________

2019
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Summary Sheet

Generic Quick Respond Drone Deploy System

Summary

In this paper, we build a generic quick respond "DroneGo" deploy system that could assist company in medicines delivery .

Because of the cost of air-dropping in emergency case, the less containers be used as well as the more medicines can be delivered are the two main requirements for the performance of our "DroneGo" system design.

This is a difficult question and we divide those challenging issues into 4 parts and use 4 models or algorithms to handle those challenge.

Firstly, we use a greedy algorithm to handle the packing problems for ISO container and cargo bay.

Secondly, we use real data from some popular drones in the market to simulate power consumption with different payload proportion.

Thirdly, we use some pre-requirements such as max roundtrip distance drones can achieve and possible best location range to reduce possible air-drop location for ISO containers. Furthermore, we design an algorithm called "Multi containers deploy algorithm based on area and demand" to help find the best location for multi containers.

Fourthly, we design an algorithm to help scan the condition of main roads and highways. The model is based on power assumption, which can help as determine a best route when consider scan main highway condition as well as achieving delivery missions.

With the help of algorithm, the packing configurations and location for 2 containers can support more than 35 day's medicine supply. With 3 containers, it can support more than 40 days' medicine supply. However, our results may have some problem, because we don't know whether the drones can be recharged and whether we need to make sure we can recycle those drones (each drone need to achieve a round trip fly).

Keywords: Drone fleet; Payload; Packing Problem

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1 Introduction

1.1 Background

When some disasters happen, how to establish a medicine supply in a short time is important. HELP, Inc. puts forward a quick response system called "DroneGo" to help establish a medicine supply. The way how "DroneGo" establish a medicine supply system is by air-dropping some ISO containers to the disaster area. Each ISO container consists of drone fleet as well as medicines. After the container is landed, it will act as a drone base. Those drones will carry medicines to medicine demand places.

Because of the cost of air-dropping in emergency case, the less containers be used as well as the more medicines can be delivered are the two main requirements for the performance of "DroneGo" system.

1.2 Challenging issues

There are many challenging issues especially when we consider the system in a more real-life way.

- Three-dimensional Packing Problem. How to pack drone fleet and medicines into the ISO container to maximum the volume utilization and how to pack medicines into the cargo bay.
- Flying distance Problem. We only know the flying time of drones without payload. However, different payload will definitely influence the flying distance. Moreover, we need to consider a roundtrip distance, which means we need to ensure the drone is able to return the container after delivery.
- Establish 3-D coordinate of Puerto Rico. A 3-D coordinate system is needed because when consider the flying route, the real flying distance is not the distance between two points in the map. The real flying distance is a result of altitude change as well as longitude and latitude change. Moreover, we also need to consider special case like mountain or cliff will block the flying route. The 3-D coordinate can also help to reduce infinite possible locations into finite possible locations when consider best location for containers.
- Drone cost performance problem. For the seven kinds of drones, how to choose those drones with highest cost performance.
- Best location chosen problem for 1,2 or 3 containers. How to choose the best location for n containers.
- Flying route problem for drones. when consider use drones to scan the condition of main highways and roads. How to choose a more helpful route based on the container location and different kinds of drones.

1.3 Our work

In this paper, we build a generic quick respond "DroneGo" deploy system that could assist company in planning the location for air-drop containers, how the drones are chosen, how to pack the container and how to choose a fly route to scan the condition of main highways and roads.

According to the challenges we mentioned above, we divide the generic quick respond “DroneGo” deploy system into 5 parts.

Firstly, we use a greedy algorithm to handle the packing problems for ISO container and cargo bay. A volume utilization is calculated here to measure different packing configures’ performances. Some conclusions in first part is very important in helping choosing drones such as : For drones with cargo bay type 2, all the combinations of medical packages can be loaded into the bay if the total weights isn’t larger than the max payload capability. For ISO container case, we also consider whether certain pack configuration can be successfully taken out from the container door since sometimes two close paralleling packets cannot be taken from the door.

Secondly, we use real data from most popular drones in the market to simulate power consumption with different payload. Most drones can only fly half time when with the maximum capability. A simulation Flying time – Payload proportion curve is calculated here for helping to choose drones with high cost-performance ratio.

Thirdly, we Establish 3-D coordinate of Puerto Rico and put altitude as an important input in choosing fly route. We use differential and integral to calculate the real flying distance and remove those block points which are mountain or cliff. Moreover, divide infinite cases into finite points can help reduce calculation cost.

Fourthly, we use some pre-requirements such as max roundtrip distance drones can achieve and possible best location range to reduce possible air-drop location for ISO containers. Furthermore, we design an algorithm called “Multi containers deploy algorithm based on area and demand“ to help find the best location for multi containers. By following the four steps in the algorithm, the best location can be chosen and measure the cost performance ratio of different drones.

Fifthly, we design an algorithm to help scan the condition of main roads and highways. The model is based on power assumption, which can help as determine a best route when consider scan main highway condition as well as achieving delivery missions.

2 Assumptions

- We regard the delivery capability as the primary requirements for “DroneGo” system because the delivery time is usually less than 15mins and differ a little.

- We assume drones can be charged per day in the container for multi-day delivery missions.

- All drones in the container, all medicines as well as cargo bay are regarded as cuboid.
- We assume the drones can maintain the same speed during flying no matter what the current payload is.
- We assume the drones will stay in a Hight above the ground during flying.

3 Model 1: Greedy algorithm for Packing problem

3.1 Model overview

This section is about how to pack different medicines into drone cargo bay as well as how to pack different drones and medicines into ISO container. In our assumptions, two kinds of cargo bays and ISO container are all considered as cuboid. Thus, putting cuboid size medicines into cargo bays and putting drones and medicines into ISO container are the same kind of problem, what we called three-dimensional packing problem (3D-PP).

The packing model is first considered in our whole workflow is because the combinations of medicines those candidate drones' cargo bay can carry is important for choosing target drones in Section 5 and 6. It is important to understand the how many medicines different cargo bay can carry. When combined with drone's max payload capability, we can have a direct thought about how many medicines one drone can take.

To solve the packing problem in three-dimensional case, we implement a greedy algorithm [2] to solve this problem.

Besides those similar in cargo bay case and ISO container case, there are some special considerations and conclusions.

For cargo bay case, according to our model's results, we find that

- For drones with cargo bay type 1, all the combinations of medical packages can be loaded into the bay if the combination meets the constraint of Table 1 except Drone A (**Space is the only constraint**).
- For drones with cargo bay type 2, all the combinations of medical packages can be loaded into the bay if the total weights aren't larger than the max payload capability (**Payload is the only constraint**).
- For Drone A, it can only load one medical package no matter its type.
  We realize when pack drones and medicines into ISO container,

For ISO container case, after putting necessary drones, we will try to put as many medicines as possible into container (the ratio of three kinds of medicines will follow daily demand). We will calculate a Space Utilization (percent) to measure the performance of different kinds of packing configurations.

3.2 Additional assumptions

To simplify this problem, some assumptions are given as follow:

- All items are cuboid shape.
- Medicines cannot be packed into drones first and then packed into container.
- The medical package is not allowed to be loaded outside the area of the drone cargo bay.
- The volume of all packed items will not change overtime and deformation is not allowed.
- Each edge of the medical package is parallel with the edge of drone cargo bay when loading or offloading in the bay.
- The centroid of one medical package is also its center of gravity and will not change overtime.

3.3 Three-dimensional packing problem

The algorithm that we use comes from Andrew Lim's work in 2001[2]. We name this packing problem as a three-dimensional packing problem (3D-PP).

The definition of 3D-PP is assuming a container *C*, and a set of cuboids $B = \{b_1, \dots, b_n\}$. The dimension of *C* is *H, W, D*. The dimension of b_i in set B is h_i, w_i, d_i[1]. The object of the problem is to select a subset of $S \subseteq B$ and assign a position to each box, $b_j \in S$ such that maximize the boxes which are in the container *C*. The idea of the algorithm comes from the process of constructing a building[3]. Let's put our container in a three-dimensional coordinate system in Figure 1. Imaging people load cuboid packages into a cuboid container in the real world, they usually load a package as the basement package. Then all the other package should not be higher than this benchmark package. When no more package can be loaded, put another basement package over the former one.

This part will introduce how the algorithm solves 3D-CPP. The algorithm will read all the parameters of container and packages from a data file. Then this algorithm will order the packages based on certain criteria. Following pseudo code presents how this algorithm work:

Main{

1. **choose_wall()**
2. *get the container information(length, width, height)*
3. *for (each package b in set B)*

   {

   1. *get package b's information(length, width, height)*
   2. *pn =* **create_package_node(package b)**
   3. **insert_package_node(package_node pn)**

   }
4. **pack()**

}

choose_wall():
This function allows user to choose which of the walls of a container to be used as the base. Basically, all the empty spaces created from one wall form an empty space list. There are at most six empty spaces. An empty space in each empty space list has its own origin and coordinate system.

create_package_node():
There are six orientations of one package which is denoted in Figure 2. For each type of package (same type of package means packages with same length, width and height), at most six package nodes will be created for them but with the same id. Each package node represents a possible orientation for one type of package. If a certain orientation is not allowed, this algorithm will simply omit the package node of that orientation.

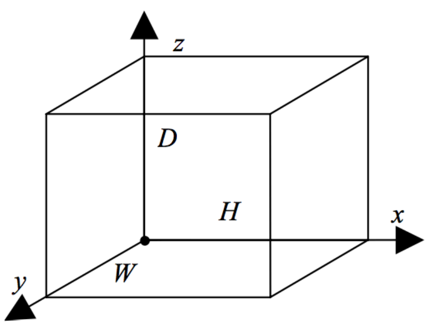

Figure.1 Coordinate System

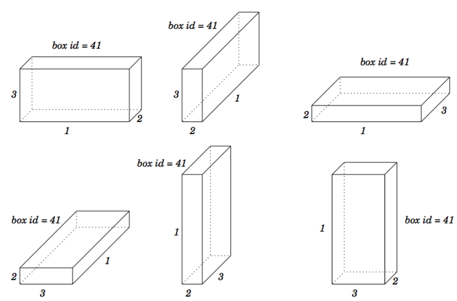

Figure.2 Six Orientations of One Package[2]

insert_package_node():
Whenever a package information is obtained from the data file, a new package node will be created and inserted to the package node list based on the function below. This function inserts the package node into a list and calculates the priority for each node. The package with highest priority can be inserted to the container first.

pack():
This function finds a most suitable empty space for each of the first *i* package nodes with the same priority. In every attempt to pack one package into the container, the algorithm finds a most suitable empty space for each of the first *i* package nodes with the same priority number, in terms of the percentage of the base area of that package occupies the base area of the empty space. Inside all these *i* pairs of package node and empty space, the algorithm finds one pair with the greatest base area occupation percentage *p*.

3.4 Packing Problem in Cargo Bay

We first evaluate and simulate the performance of two types of drone cargo bays loading the three demanding medical packages.

We implemented the algorithm mentioned above using C programming language. Based on the drone cargo bay dimensions and the medical package dimensions, this paper used them as input data to determine the capability of each drone cargo bay type. According to Attachment 5, there are totally 3 types of medical package with different weights and dimensions. According to Attachment 2 and 3, seven types of drones equipped with two different types of drone cargo bays are able to load the medical packages in the constraint of max payload capability and dimensions of the drone cargo bay. Our experiment was divided into two parts. The dimensions of the drone cargo bay are considered first. Using the algorithm introduced above, the loading capacity of each type of drone cargo bay can be determined. Table 1 and Table 2 present the loading capacity of drone cargo bay type 1 and drone cargo bay type 2.

Number of MED 1 Loaded	Number of MED 2 Loaded	Number of MED 3 Loaded	Space Utilization of Drone Cargo Bay
2	0	0	87.5%
0	4	0	71.4%
0	0	2	60%
0	2	1	65.7%
1	2	0	79.4%
1	0	1	73.8%

Table 1. Loading Performance of Drone Cargo Type 1

Number of MED 1 Loaded	Number of MED 2 Loaded	Number of MED 3 Loaded	Space Utilization of Drone Cargo Bay
6	20	5	89.8%
15	0	0	76.5%
12	12	0	86.25%
0	0	25	87.5%
11	0	7	80.6%
0	12	20	95%
0	48	0	96%

Table 2. Loading Performance of Drone Cargo Type 2

We computed all the possibilities of loading different types of medical packages in a drone cargo bay trying to utilize most space of the drone cargo bay. Each row of Table 1 and Table 2 illustrates the number of medical packages of each type that can be loaded. And the last element of each row is the percent of space utilization of the drone cargo bay when loading specific combination of medial packages.

At this moment, it seems that drone cargo type 2 is much better than type 1 in the performance of loading medical packages. However, the constraint of max payload capability wasn't considered in our experiment. After considering the constraint of max payload capability of each drone type, the drone cargo bay's space is the main constraint for drone cargo type 1. The max payload capability is the main constraint for drone cargo type 2.

Based on our experiment results, for the drones with drone cargo type 1, the space of drone cargo bay is the main constraint. According to our experiment results, drone cargo bay type 2 can load eleven type 1 medical packages and seven type 3 medical packages at the same time. According to Attachment 5, type 1 medical package is as weigh as type 2 medical package. And type 2 medical package is smaller than type 1 medical package. So all the drones with drone cargo bay type 2 can load all the medical packages if the whole weights are less the max payload capability.

Conclusion

- For drones with cargo bay type 1, all the combinations of medical packages can be loaded into the bay if the combination meets the constraint of Table 1 except Drone A (**Space is the only constraint**).
- For drones with cargo bay type 2, all the combinations of medical packages can be loaded into the bay if the total weights isn't larger than the max payload capability (**Payload is the only constraint**).
- For Drone A, it can only load one medical package no matter its type.

4 Model 2: Power consumption model with different payload.

4.1 model overview

Choosing different candidates of drones is very essential in our system because of their performance in payload capability, delivery distance and cargo bay type are different.

This section uses real data from most popular drones in the market to simulate power consumption with different payload. Most drones can only fly half time when with the maximum capability. A simulation Flying time – Payload proportion curve is calculated here for helping to choose drones with high cost-performance ratio.

We further use the Flying time – Payload curve to calculate the roundtrip distance drones can fly with full payload.

4.2 Additional assumptions

- We assume the drone will remain the same flying speeding with or without the payload.
- We assume the Flying time – Payload curve is similar for all candidate drones in our case.
- We assume the mass of drones is in direct proportion to maximum payload capability.

4.3 how model works

The maximum flight time of drone is different when it carries with cargo of different weight. Obviously, drones will fly longer distance if they don't carry any cargo whereas they cannot not reach same distance if they carry with extra payload. In DroneGo system, drones need to carry medicine and fly from the place where standard ISO container is dropped to one (or some) of five destinations. On the way to destination, these drones carry with medicine, so we need to consider how payload affects flight time of drone.

We find that most drone vendors don't give such detail in their product page, but we find that there's some discussiones about flight time vs. payload on forum [4]. The following Table 3 shows a set of experiments in their discussion.

Flight time (min)	40	37	35	30	18
Payload (lb)	0	1.1	2.2	4.4	12.1

Table 3. Flight time (min) vs weight(lb)

Considering that different drone may have different net weight and different maximum flight time, we choose to find the relationship between how flight time is affected by payload percentage. The new chart we get from statistic data in chart above shows how payload percentage affects flight time as following.

Payload	0	0.09090909	0.18181818	0.36363636	1
Flight time	1	0.925	0.875	0.75	0.45

Table 4. Flight time(% of empty payload) vs. Payload (% of full payload)

After trying different fit formula, We choose to use quadratic fit to simulate the relationship between flight time and payload weight, because it is the simplest polynomial regression equation with high coefficient of determination ($R^2 > 0.99$) (shown in Figure 3)

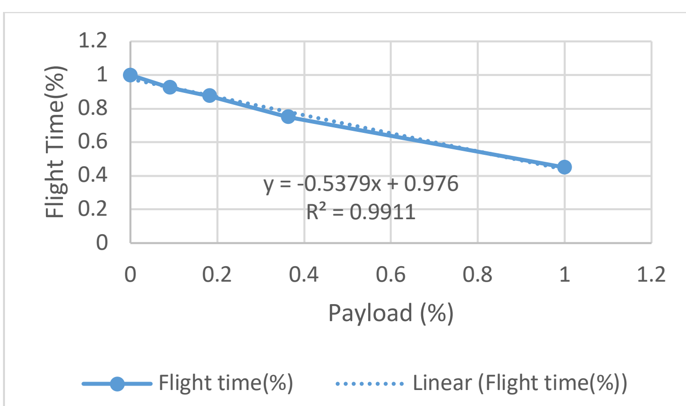

Figure.3 Flying time – Payload proportion curve

According to the real case data, a planning trip for drone should not exceed 95% power supply otherwise the drone may not be able to make it since there are many uncertainties during the fly. We define a function called MaxRound(p, s, t, m) to calculate the max distance (meter) a drone can achieve for a round trip fly within 95% of overall power.
Here p stands for the actual payload(lbs.), s stands for the speed(km/h), t stands for max flying time without payload (min), m stands for its max payload capability(lbs).

$$\mathrm{MaxRound(p,s,t,m)} = s * \frac{0.95 * t}{1 + \frac{1}{-0.5379 * \frac{p}{m} + 0.976}} * \frac{1000}{60}$$

Drones	Longest distance drones can reach with full payload (meter)
A	6752.81042
B	15242.05781
C	10804.49667
D	5209.31090
E	4341.09241
F	9145.23468
G	4939.19848

Table 5. Longest distance drones can reach with full payload (meter)

For example, drone B can fly 40 min without a cargo and its max payload is 8 lbs. However, with full payload, the maximum distance drone B can achieve is only 15242 meter as shown in Table 5.

5 3-D coordinate of Puerto Rico

5.1 Establish the coordinate system

Before determining the best route for drones, we first need to model Puerto Rico to better describe its landform. We put the Puerto Rico into coordinate axis, we use (x, y) to present different location of Puerto Rico while we set the origin (17.938386°, -67.276150°) as shown in the Figure 4. We choose the origin as one point in the southwest Puerto Rico in order to make sure (x, y) is always positive pairs. We will use Point A to represent Caribbean Medical Center, Fajardo; Point B to represent Hospital HIMA, San Pablo; Point C to represent Hospital Pavia Santurce, San Juan; Point D to represent Puerto Rico Children's Hospital, Bayamon and Point E to represent Hospital Pavia Arecibo, Arecibo.

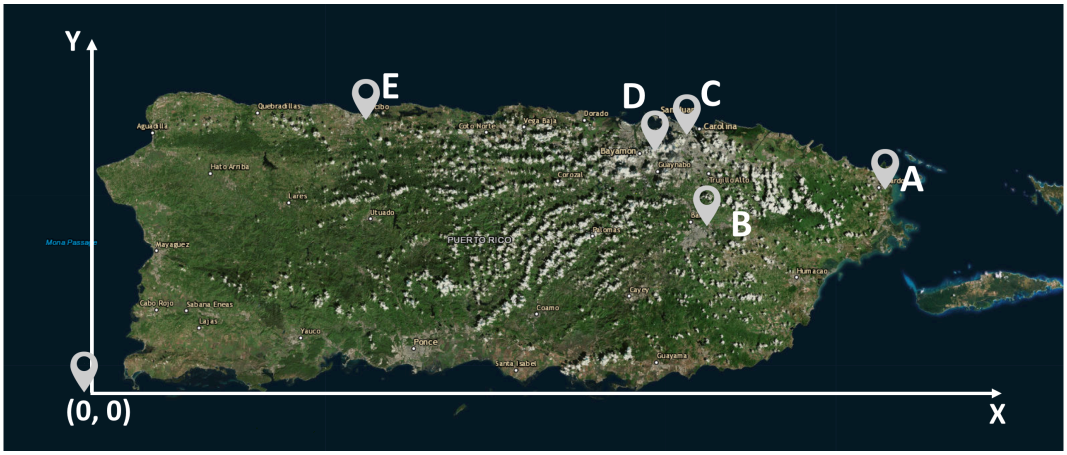

Figure 4. Coordinate axis of Puerto Rico

We first need to find the axis scale for latitude and longitude. We choose these axis scale to make sure $\Delta x = 500\ meter$ and $\Delta y = 500\ meter$. In this way, we divide the whole Puerto Rico as infinite points. In the next section, when we consider the best position, we will only consider those points whose x and y are both integer to save time.

Φ	Δ1° LATITUDE	Δ1° LONGITUDE
0°	110.574 km	111.320 km
15°	110.649 km	107.551 km
30°	110.852 km	96.486 km
45°	111.133 km	78.847 km
60°	111.412 km	55.800 km
75°	111.618 km	28.902 km
90°	111.694 km	0.000 km

Table 6. The real distance of 1-degree latitude and longitude in different degree.

The real length of 1 degree of latitude changes a little for different latitude, while the longitude changes a lot. The latitude and longitude of center of Puerto Rico is 18.2208° N, 66.5901° W. According to Table 6 [6,7] the scale for latitude as:

$$R_{LA} = \frac{\mathrm{y2-y1}}{\text{real distance in latitude}} = \frac{500}{110650\ \text{meter}}$$

And the axis scale for longitude is:

$$R_{LO} = \frac{\mathrm{x2-x1}}{\text{real distance in longitude}} = \frac{500}{55800\ \text{meter}}$$

Thus in our coordinate axis, the distance between (x1, y1) and (x2, y2) are

$$d = \sqrt{(x_2 - x_1)^2 {R_{LA}}^2 + (y_2 - y_1)^2 {R_{LO}}^2}$$

The (x, y) of point in latitude and longitude pair (m, n) can be calculated by

$$x = (\mathrm{m} - \mathrm{m}_0)/R_{LO}$$
$$y = (\mathrm{n} - \mathrm{n}_0)/R_{LA}$$

Where (m0, n0) are the latitude and longitude of origin (17.938386°, -67.276150°).

5.2 Altitude in real case

Besides turning two-dimension latitude and longitude into (x, y) pair, we also consider the altitude of different points. The altitude here is important because

1) The real distance drone fly should be calculated by altitude change and straight-line distance as shown in Figure 2. Drones usually fly in a certain height of ground. Thus the real flying distance will be different from the straight-line distance. We calculate the real flying distance by the differential and integral. As shown in Figure 6, when the drone route is a sequence like $< (x_0, y_0), (x_1, y_1), (x_2, y_2) \ldots (x_m, y_m) >$, we calculate real flying distance for certain route by

$$\mathrm{D} = \sum_{n=1}^{m} \sqrt{(x_n - x_{n-1})^2 {R_{LA}}^2 + (y_n - y_{n-1})^2 {R_{LO}}^2 + (A(x_n, y_n) - A(x_{n-1}, y_{n-1}))^2}$$

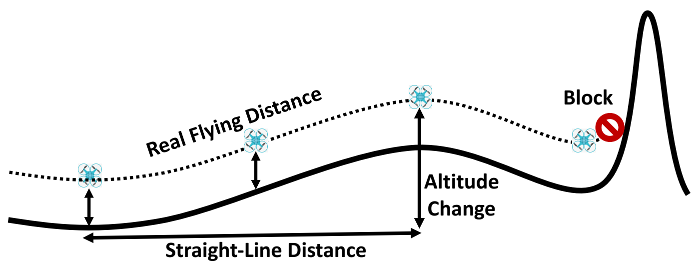

Figure 5. Example of flying route in real case

2)As shown in Figure 5, drones cannot fly in a route where there are some block points like high mountains whose altitude sharply changes.

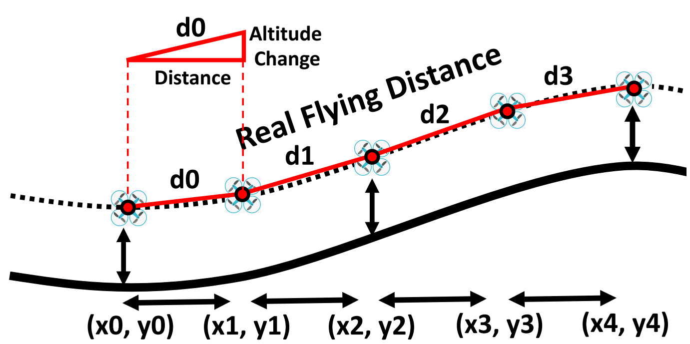

Figure 6. Real flying distance calculation based on calculus thought

In order to get the altitude of different points, we use Google Maps Platform API [5] to get the altitude of different points.

6 Best location for single container

When not consider using onboard video cameras to assess major highways, there are some restricts for best location of a single container.

6.1 One possible Convex Polygon Area

- The best location for container must within a convex polygon area which consists of those medical package demand places.

As shown in Figure 7 the best position for either a single container or multiple containers must within the Convex polygon area which includes all 5 medical package demand places with the minimum area. In our case about Puerto Rico, the convex polygon is a quadrangle. When a point satisfied with the following four equations, the point will be within the quadrangle and is a possible best position for container. However, a point within the quadrangle doesn't mean that point is able to achieve the drone delivery goal. This is only a prerequisite for reducing calculation complexity.

$$y - 0.59524x + 20.73810 \geq 0 \ldots\ldots \text{eq1(x,y)}$$
$$y + 0.52174x - 181.43478 \leq 0 \ldots\ldots \text{eq2(x,y)}$$
$$y + 0.09459x - 123.77027 \leq 0 \ldots\ldots \text{eq3(x,y)}$$
$$y + 0.71795x - 161.79487 \geq 0 \ldots\ldots \text{eq4(x,y)}$$

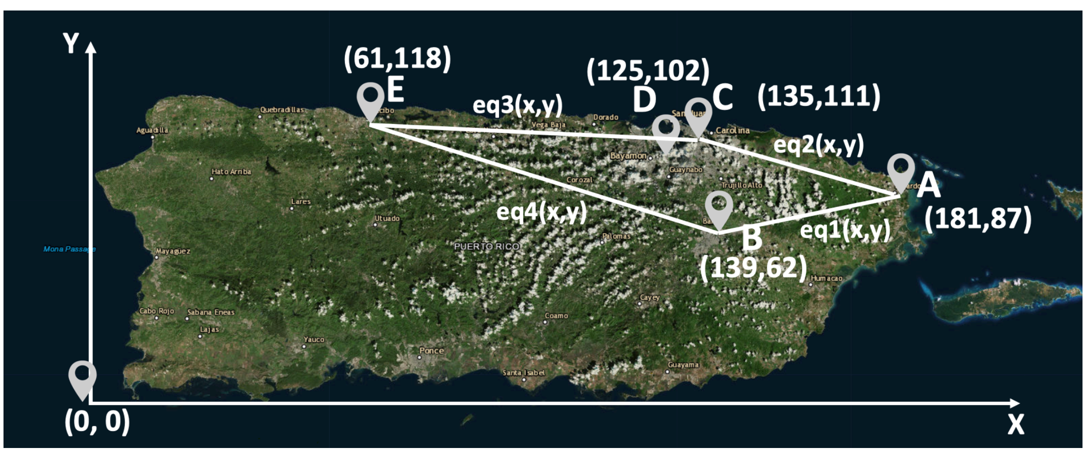

Figure 7. Best position restrictions

Note that even we set $\Delta x = 500\ meter$ and $\Delta y = 500\ meter$ in our coordinate axis, the number of points within the quadrangle area and whose (x,y) is integer pair is 6897. There is a balance between accurate and calculation complexity. We use multithreading to handle this problem in simulation part.

	AB	AC	CE	BE
Distance (meter)	24438.69882	25942.24354	37165.17187	48010.41554

Table 7. Distance between points

6.2 Restriction based on max round trip distance

- For each medical package demand place, the possible delivery range is a circle where the demand place is the center and radius are the maximum distance those drones can fly when the payload is the heaviest medicine required for the place. The best location for a single container must within the overlap area of those circles.

When only load one packet of medicine, either bay 1 and bay 2 can load a single MED1, a single MED2 or a single MED3.

Let's take Point D (Puerto Rico Children's Hospital) as an example. Point D needs 2 MED1, 1 MED2 and 2 MED3 per day. MED1 is 2 lbs. per packet, MED2 is 2 lbs. per packet and MED3 is 3 lbs. per packet. The heaviest medicine is MED3. So, no matter which kind of drones the container has and no matter what's the payload of those drones, the longest distance those drones can reach is only carrying one packet of the heaviest medicine (MED3) and able to fly a round trip. Here the radius is 21834meter for Point D.

According to

$$\mathrm{MaxRound(p,s,t,m)} = s * \frac{0.95 * t}{1 + \frac{1}{-0.5379 * \frac{p}{m} + 0.976}} * \frac{1000}{60}$$

The longest distance drone can reach is shown in Table 8 and the possible location radius for Point A-E are shown in Table 9.

Drones	Longest distance drones can reach from Point A, B, D (meter)	Longest distance drones can reach from Point C, E (meter)
A	7534.65163	8882.30426
B	21834.22054	22863.82256
C	16406.10562	16791.71562
D	7752.16203	7995.53828
E	6623.23514	6766.85676
F	14242.00615	14442.18878
G	7658.90658	7778.59762

Table 8. Longest roundtrip Distance for different drones

Place	Radius(meter)
P_A	21834
P_B	21834
P_C	22863

P_D	21834
P_E	22863

Table 9. Radius for possible location circle.

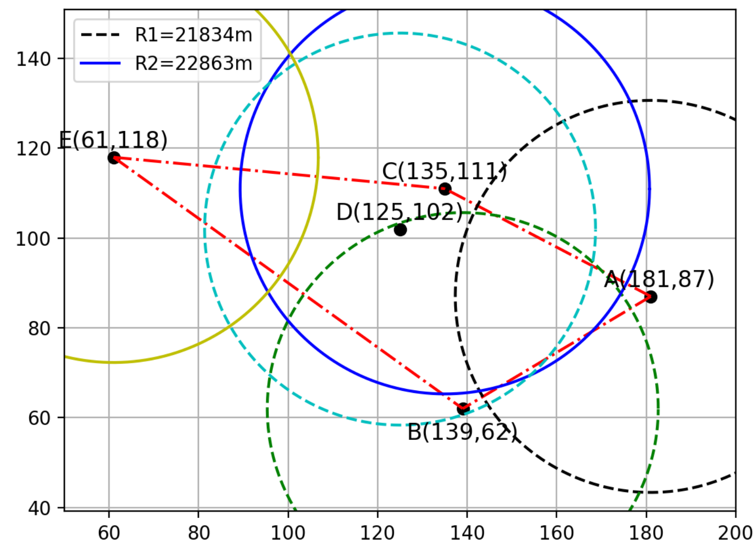

Figure 8. Possible location and location restrictions.

6.3 Tradeoffs of Choosing Single Container

As shown in Figure 8, there is no possible location for one single container to cover all 5 points. Then there will need tradeoffs here. There is an area which is an overlap of circles of Point A, B, C, D. At the same time the location E has the minimum medicine demand, then it is better to cover Point A, B, C, D first. In this paper, we will talk more about how to use multi containers to cover all the points.

7 Multi containers deploy algorithm based on area and demand

7.1 Algorithm overview

When a single container is not enough to cover the whole area, multi containers should be used for deploying the system. Since there is no weight limit for ISO container, the goal here is to find a combination of drones which can satisfy daily medicine delivery demands and the sum of their volumes is minimum. After putting those drones into containers, try to put as many medicines as possible into container (the ratio of three kinds of medicines will follow daily demand). Besides that, we will calculate a Space Utilization (percent) to measure the performance of different kinds of packing configurations.

To measure the performance of certain container packing configurations, we define a performance function $P(c1, \dots, cn)$. The goal is to find the highest $P(c1, \dots, cn)$.

$$P(c1, \dots, cn) = N * 100 + Space\ Utilization \text{ (n = 1,2,3)}$$

Where N is the number of days the packing configurations can support.

In order to find the combination of drones which can satisfy daily medicine delivery demands and the sum of their volumes is minimum.

We give priority to delivery all medicine a Point need daily by one drone. We define a function $D(n, d, V)$ to measure the cost performance of different drones for different medicine demand places. Here n stands for the total weight of daily medicine demand for certain medicine demand place, d stands for the roundtrip distance the drone can fly when the payload is n; V here stands for Volume of this drone. The higher d and the smaller V will count for a higher $D(n, d, V)$, which means this kind of drone will be chosen in priority.

When choose the best locations for containers, we try to let different ISO containers to in charge of different areas. For example, we bind Point C and Point D together since the distance between them is so short when compared to distances between other points. We divide the five medicine points into three areas. One area contains Point C and Point D, one area contains Point A and Point B and the rest area contains Point E only.

It is obvious the best location for different area must within the lines CD, AB or Point E. The exact location will be calculated by medicine demand proportion of two points.

7.2 Additional assumptions

- The drones can be recharged once daily in the ISO container.
- The power of the drones will be full before they fly to deliver the medicine every day.
- There is no priority in the five medicine demand places.
- One container is in charge of one area.

7.3 Multi containers deploy algorithm based on area and demand

We put forward a multi containers deploy algorithm based on area and demand. The algorithm consists of three steps:

Step1: Divide N areas. all medicine demand places (U = {PA, PB, PC, PD, PE} in our case) into N groups (G1, G2, … GN), where N is the number of containers. There is no overlap in different groups and the union of Points in N groups is the set of all medicine demand places.

$$\mathrm{G1} \cup \dots \cup \mathrm{GN} = \mathrm{U}$$

Step2: Calculate the location for container in each area. Each container will in charge of one group. If the group only contain one point, then the point itself is the best location for the container which is in charge of the area. When the group contain two points, the best location must in the Line of those two points. The exact location will be calculated by medicine demand weight proportion of two points. When there is more than 2 points, a weighting sum of distances towards those points will calculated.

Step3: Choose proper drones. The goal for step 3 is to choose the proper drones with the highest cost performance function $D(n, d, V)$. To choose drones in the container, we give priority to delivery all medicine a Point need daily by one drone. We then calculate a function $D(n, d, V)$ to measure the cost performance of different drones for certain Point. n is the total weight of daily demand medicines for Point X; d stands for the roundtrip distance the drone can fly when the payload is n; V here stands for Volume of this drone. The higher d and the smaller V will count for a higher $D(n, d, V)$, which means this kind of drone will be chosen in priority for the point with weight of daily demand medicine = n.

Step4: Maximum Pack configuration. Repeat Setp3 if the result cannot be packed into one container using the Packing Model in Section 3. If the drones are able to be packed into the container then try to maximum container utilization.

7.4 When use 2 containers

We follow our algorithm to find the best locations for two containers.

Step1: Divide all medicine demand places (U = {PA, PB, PC, PD, PE} in our case) into 2 groups (G1, G2).

Point E is a special point since it is far away from other points. According to the Possible Container Location Model in Section 6. The possible location for Container 1 should within the PE circle. At the same time, the daily demand for E is smallest while the daily demand for D is the largest. So Group 1 is a {PE, PD}. Group 2 is {PC, PA, PB}.

	Point A	Point B	Point C	Point D	Point E
Medicines weight (lbs.)	5	5	4	12	2

The distances between Point D and other medicine demand place are

	CD	DE	AD	BD
Distance (meter)	6726.81202	32984.84500	28987.06608	21189.62010

Step2: Calculate the best location for Container1 in two points group G1 {PE, PD} and the best location for Container2 in three points group G2 {PC, PA, PB}.

There are two requirements when choose the location C1 for Container1. One is the location C1 should within PE circle and circle PD. The other requirement is the best location must in the line DE.

Besides the two requirements, the ratio of distance between C1, D and the distance between C1, E should equal to ratio of medicines weight of D and E.

$$\frac{Distance\ of\ C1, D}{Distance\ of\ C1, E} = \frac{12\ lbs.}{2\ lbs.}$$

When choose C2 for Container2. The weighting total distance from C2 to Point A, B, C should be minimum.

MIN($R1 * Distance(C2, A) + R2 * Distance(C2, B) + \ R3 * Distance(C2, C)$)
Where

$$R1 = R2 = \frac{5}{14}, R3 = \frac{4}{14}$$

The location of C1 is (105,107) according to our calculation, whose latitude and longitude is (18.42190, -66.33534). The location of C2 is (153,83), whose latitude and longitude is (18.31346, -65.90523).

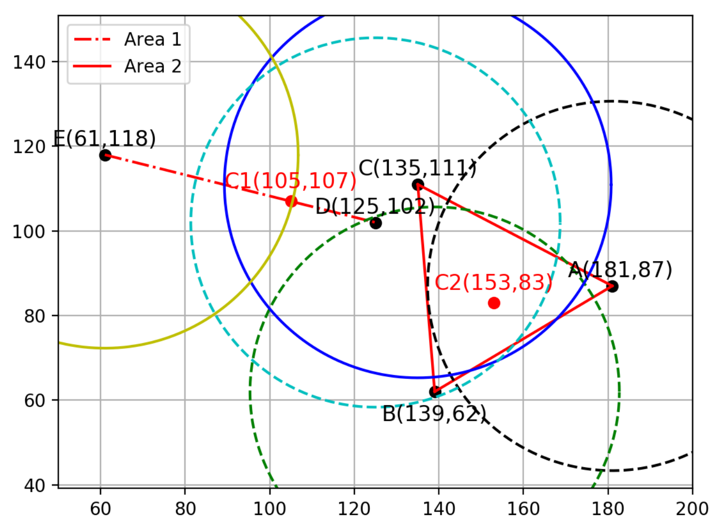

Figure 9. Two groups and the location for Container 1 and 2

Step3: Choose the proper drones with the highest cost performance function $D(n, d, V)$.

$$D(n, d, V) = \frac{\mathrm{d(n)}}{V}$$
$$\mathrm{d(n)} = \mathrm{MaxRound(n, s, t, m)}$$

If d(n) is less than the distance between container and Point X, then D(n, d, V) is 0.

	Drone A	Drone B	Drone C	Drone D	Drone E	Drone F	Drone G
Point A	N/A	***	**	N/A	N/A	*	N/A
Point B	N/A	***	**	N/A	N/A	*	N/A
Point C	N/A	**	*	N/A	N/A	N/A	N/A
Point D	N/A	*	**	N/A	N/A	***	N/A
Point E	N/A	*	N/A	N/A	N/A	N/A	N/A

For certain Point X, the more "*" one kind of drone has, the higher the priority to choose this kind of drone.

Step4: Check whether drones can be packed and maximum the utilization of container.

For Container 2, we need 3 Drone B. For Container 1, we need 1 Drone F and 1 Drone B.
If the drone can be recharged in container every day, then it can take more than 300 day's demand of medicines. However, if we need to take N Drone F for N days in the container, then the container can still supply more than 35 day's medicine need. While the utilization of containers are all larger than 80%.

However, our results may have some problem, because we don't know whether the drones can be recharged and whether we need to make sure we can recycle those drones (each drone need to achieve a round trip fly).

7.5 When use 3 containers

Step1: Divide all medicine demand places (U = {PA, PB, PC, PD, PE} in our case) into 2 groups (G1, G2, G3). G1 = {PC, PD}, G2 = {PA, PB}, G3 = {E}.

Step2: Calculate the best location for Container1 in two points group G1 {PC, PD} and the best location for Container2 in three points group G2 {PA, PB}.

All groups have less than 3 points, thus we use the similar method to calculate Containers' locations here.

The location of C1 is (128,104) according to our calculation, whose latitude and longitude is (18.40835, -66.12925). The location of C2 is (160,75), whose latitude and longitude is (18.27731, -65.84251). The location for C3 is (105, 107), whose latitude and longitude is (18.42190, -66.33534).

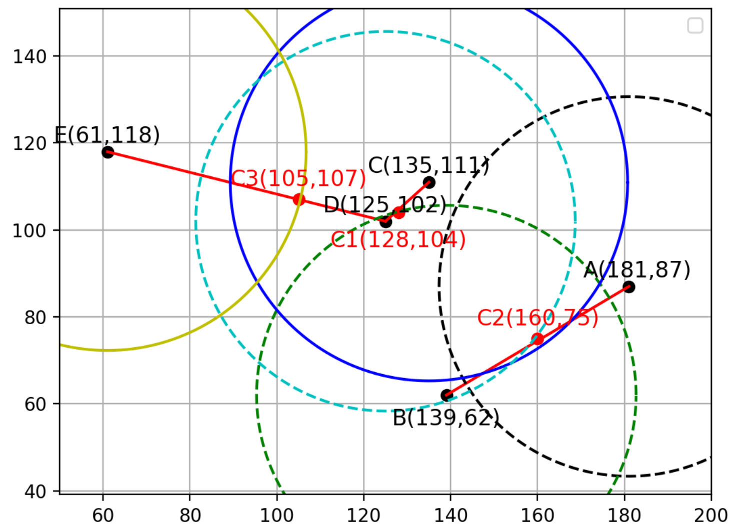

Figure 10. Three groups and the location for Container 1, 2 and 3

Step3: Choose the proper drones with the highest cost performance function $D(n,d,V)$.

The priority in choosing drones is almost the same in Section 7.4. The difference is that for Container 1, only one drone is needed. Drone F is able to carry 2 Med1, 1 Med2 and 2 Med3 (12 lbs) and fly to Point D and then return to C1. The remaining power is able to supply Drone F to take 1 Med1 and 1 Med1 (4lbs) to Point C and then return with no payload.

Step4: Check whether drones can be packed and maximum the utilization of container.

For Container 1, we only need one Drone F per day. For Container 2, we need 2 Drone B per day. For Container 3, we need 1 Drone F and 1 Drone B per day.
If the drone can be recharged in container every day, then it can take more than 300 day's demand of medicines. However, if we need to take N Drone F for N days in the container, then the container can still supply more than 45 day's medicine need. While the utilizations of containers are all larger than 80%.

However, our results may have some problem, because we don't know whether the drones can be recharged and whether we need to make sure we can recycle those drones (each drone need to achieve a round trip fly).

8 Model 3: plan model based on power assumption

8.1 Model overview

This section mainly discusses on the route planning of drone fleet to cover as much area as possible after medicine delivery. Specifically, the goal of this model is to find drones' optimal flying routes that satisfy three condition:

1) The drone must be able to deliver medicine from container to destination
2) The drone must be able to return container after road assessment
3) The drone stays over major highways and roads at its maximum possible route guarantees safe return, in another word, drones needs to return before battery is exhausted

8.2 Notation

Notations	Descriptions
D	Total distance of drone flight
D_i	Flight distance in segment i
(x_i, y_i, z_i)	Geometry coordinate of location i
C_i	Energy consumption for segment i
l_i	Weight of medicine needed in destination i
L	Total weight of medicine

8.3 Additional assumption

- Destination is conjunctive to major highways and roads
- For certain destination, the number of its conjunctive road is finite
- A highway/road destroyed or partially breaks during hurricane is still considered accessible for drones
- A drone only assesses places where it flies over.

To explain these assumptions, all these assumptions are made by common sense and they do simplify our model for flight route planning. By first and second assumption, we only need to consider possible routes with an upper bound of number of roads conjunctive to the city plus one, which indicates flying back directly without any road assessment. With third assumption, we don't need to consider the case that road is destroyed, and this assumption always holds because drones can fly over destroyed roads or broken point of roads. Forth assumption helps us reduce the search space that a drone can assess during flight.

8.4 Route plan model based on power assumption

Before starting to find optimal planning route for drone fleet, we need to determine the route model for drone first. As illustrated in requirement document, the drone needs to carry medicine from container where it starts its flight to the destination where medicine should be dropped. While a drone guarantees medicine will be delivered to destination, it should assess highways and roads as much as possible. Also, it needs to ensure that drone is able to fly back to container before it uses up all energy.

A route model is a circular line on the map that drone follows to finish delivery task and assess as much road as possible. In formal, it represents as following

$$\mathrm{D} = \sum_{i=1}^{n} \sqrt{(x_i - x_{i-1})^2 + (y_i - y_{i-1})^2 + (z_i - z_{i-1})^2},$$

Where (x_0, y_0, z_0) and (x_n, y_n, z_n) is the location of container. We cut the whole route as a set of straight lines that drones follow to fly. This is our basic model for route planning, later we will discuss about how to choose size of each segment and our macroscopic strategy on choosing route.

Selection of route

The problem of route selection is crucial in our solution as a better route selection makes drone fly longer distance. The route selection includes two parts. First part is order of work drones have to do. Second part is how to simulate real road with random curve by a set of straight routes.

As a matter of payload, the energy consumed per unit distance varies when drones fly with different weight. A drone usually flies shorter distance if it carries heavier payload. Considering that, we draw a conclusion that drone should finish its delivery task as soon as possible and do road assessment task later if it still has enough energy left. In other word, the first segment of drone route must be the direct route (may go around if there's peak on the way of flight at direct distance), and drone fly along road to make assessment later.

In the second part, we need to find a solution to simulate curved road by segments of straight line. We can do such simulation because drones fly on the sky so there's no spatial limitation for drones, and by making such simulation, we can use computer to simulate real flight route for drones. Here's the algorithm for drone flying along road:

1) Drone starts from delivery destination and fly along the direction of the start point at the road
2) We sample one point per meter
3) For every ten sample, we use linear regression to find a line and cut the line by normal line of curve line from first and last sampling point.
4) In between lines we get from 3), we connect consecutive lines by connecting end point of previous line and start point of later line by a straight line.

Find optimal route

To find optimal route for drone, we have three constrain:

1) Drone must deliver medicine

2) Drone must be able to return to container
3) Drone fly as much road as possible

We mark the first part of route from container to destination as D_1, second part along the road as D_2, and third part returning to container as D_3, then we can express percentage of energy consumption for each part along with a function expressing maximum flying time with certain load l, $f(l)$, by formula:

$$C_1 = \frac{D_1}{f(load)}$$

$$C_2 = \frac{D_2}{f(0)}$$

$$C_3 = \frac{D_3}{f(0)}$$

And total energy consumption is

$$\mathrm{C} = \sum_{1}^{3} C_i$$

Notice that load function $f(l)$ is not related to distance, and the distance of first part is constant once container is dropped at certain location. Therefore, we can get maximum distance if we let drone consume all energy. Meanwhile, we know that the maximum percentage of battery energy consumption is 100%, thus we can find maximum distance with following equation:

$$\frac{D_1}{f(l)} + \frac{D_2 + D_3}{f(0)} = 1$$

Considering one drone might deliver medicine to multiple destinations, we can make formula above more general:

$$\sum_{i=1}^{n} \frac{D_{1.i}}{f(L - \sum_1^{i-1} l_i)} + \frac{D_2 + D_3}{f(0)} = 1$$

Where L is total weight of medicine, and l_i is weight of medicine needed in i_{th} destination. With this equation, we can calculate the maximum distance drone can fly on road, which is the optimal planning route for drones.

9 Strengths and limitations

Strength:

- We build a generic quick respond "DroneGo" deploy system that could assist company in planning the location for air-drop containers, how the drones are chosen, how to pack the container and how to choose a fly route to scan the condition of main highways and roads.

Our model can quantitatively calculate the possible area drifting debris will be after a certain time delay.

- Our solutions consider a lot of real -case problem, which can make sure the system will work well when put into real use.
- All the simulations in our paper are generic. In the actual search, company can calculate precise data by changing input parameters.

Limitations:

- There are still many factors can be added into our simulation such as drone go to more than 2 points at the same time. Also we don't know whether those drone can be recharged or not.
- We didn't prove a best solution, instead we use different methods to reduce possible location and find a relatively best solution in this paper.

10 Conclusions

In this paper, we build a generic quick respond "DroneGo" deploy system that could assist company in planning the location for air-drop containers, how the drones are chosen, how to pack the container and how to choose a fly route to scan the condition of main highways and roads. Our deploy system consists of 5 parts. We use a greedy algorithm to handle the packing problems for ISO container and cargo bay. We use real data from most popular drones in the market to simulate power consumption with different payload. We Establish 3-D coordinate of Puerto Rico and put altitude as an important input in choosing fly route. We use some pre-requirements such as max roundtrip distance drones can achieve and possible best location range to reduce possible air-drop location for ISO containers. Furthermore, we design an algorithm called "Multi containers deploy algorithm based on area and demand" to help find the best location for multi containers. We also design an power based algorithm to determine a better flying route.

11 Memo to HELP, Inc. CEO.

Dear HELP, Inc. CEO,

I am so glad to have the chance to talk to you about our thought in the “DroneGo” system.

Because of the cost of air-dropping in emergency case, the less containers be used as well as the more medicines can be delivered are the two main requirements for the performance of “DroneGo” system. This is also the key focus on our suggestions.

This is a difficult question and we divide those challenging issues into 4 parts and use 4 models or algorithms to handle those challenge.

Firstly, we use a greedy algorithm to handle the packing problems for ISO container and cargo bay.

Secondly, we use real data from most popular drones in the market to simulate power consumption with different payload proportion.

Thirdly, we use some pre-requirements such as max roundtrip distance drones can achieve and possible best location range to reduce possible air-drop location for ISO containers. Furthermore, we design an algorithm called “Multi containers deploy algorithm based on area and demand“ to help find the best location for multi containers.

Fourthly, we design an algorithm to help scan the condition of main roads and highways. The model is based on power assumption, which can help as determine a best route when consider scan main highway condition as well as achieving delivery missions.

We also Establish 3-D coordinate of Puerto Rico and put altitude as an important input in choosing fly route. We use differential and integral to calculate the real flying distance and remove those block points which are mountain or cliff. Moreover, divide infinite cases into finite points can help reduce calculation cost.

With the help of algorithm, the packing configurations and location for 2 containers can support more than 35 day’s medicine supply. With 3 containers, it can support more than 40 day’s medicine supply. However, our results may have some problem, because we don’t know whether the drones can be recharged and whether we need to make sure we can recycle those drones (each drone need to achieve a round trip fly).

It is a really good experience for participating the system design!

Best!

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