xS3D lab fall seminar

Analysis of the resources required for persistent robotic service

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Contents

- Motivation
- Literature review
- Problem description
- Mathematical model
  - Embedded Petri net model
- Solution approaches
  - Enumeration method
  - Heuristic approach
- Concluding remark

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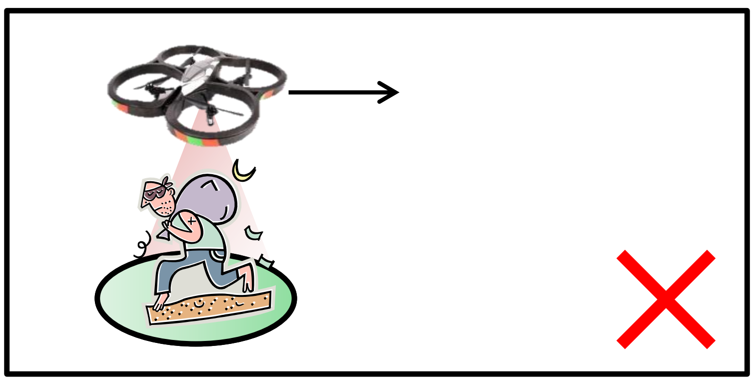
Motivation

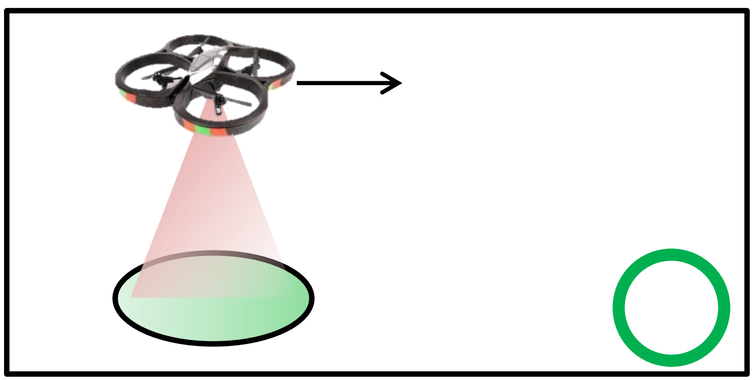
- Unmanned aerial vehicles(UAVs) are used various fields
- Recently, companies have interest about UAV
  - Amazon (Delivery service)
  - SECOM (Surveillance)
  - Gofor (Tracking & record service)

- Companies use relatively small size of UAV due to economic reason
- Small size UAV has fuel limitation when it provides persistent service

Motivation

- What is the persistent service?
  - UAV has fundamental limitation : Fuel capacity
  - Services such as patrol, monitoring, and surveillance require continuous service.
  - Surveillance example





Motivation

- **<u>Objective : deriving the number of resources & service path to provide persistent UAV service with multiple immobile customers</u>**

- Example
  - Surveillance of disaster(biohazard) site
  - Temporary traffic enforcing during holiday

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Literature review

- Literature review

Literature	Persistent service	Resource Analysis	Path planning	Stochastic	note
Muller(1983)		√			
Min(2010)		√		√	
Enright(2005)			√	√	
Bethke(2005)	√				Immobile customer
Valenti(2007)	√	√			Not systematic approach
Suzuki(2012)		√			System coverage concept
Song(2013)	√				Moving customer
Kim(2014)	√				System design
This research	√	√	√		

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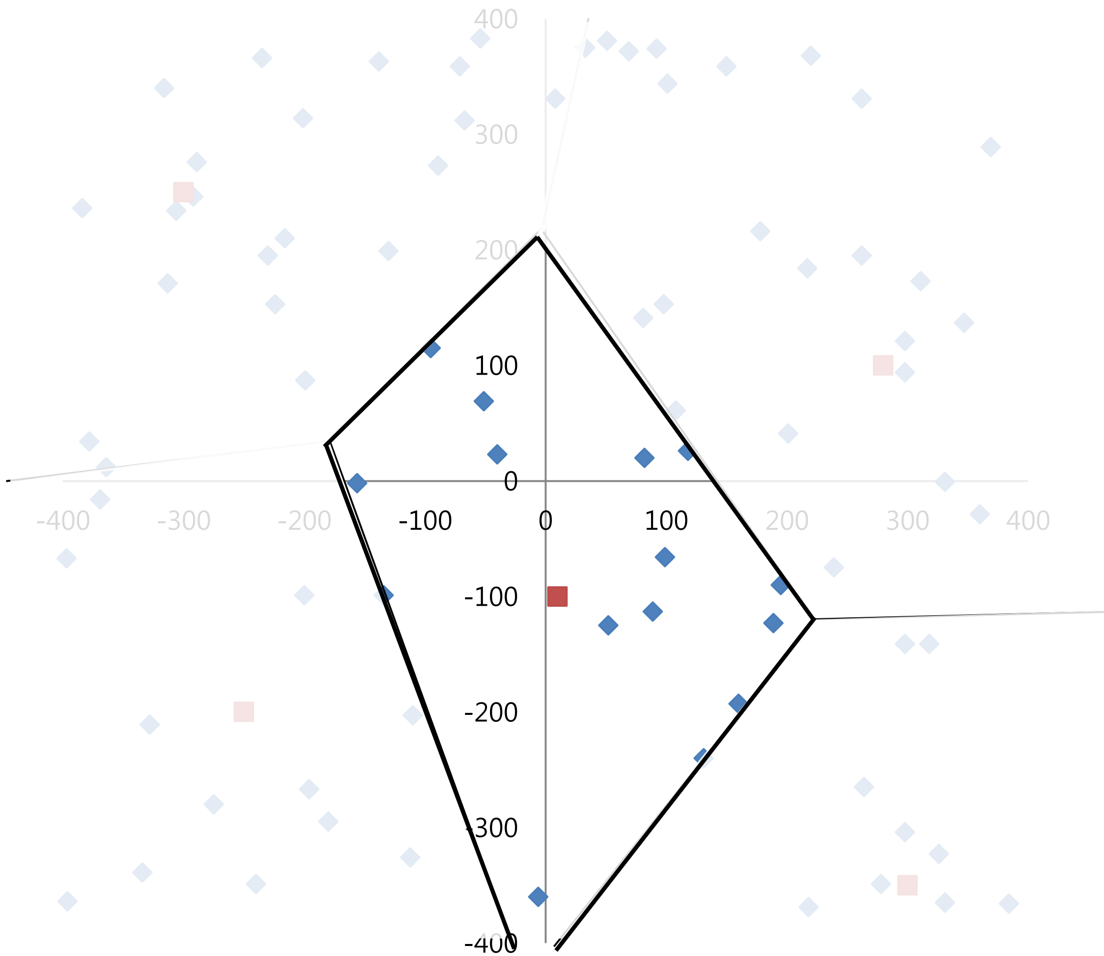
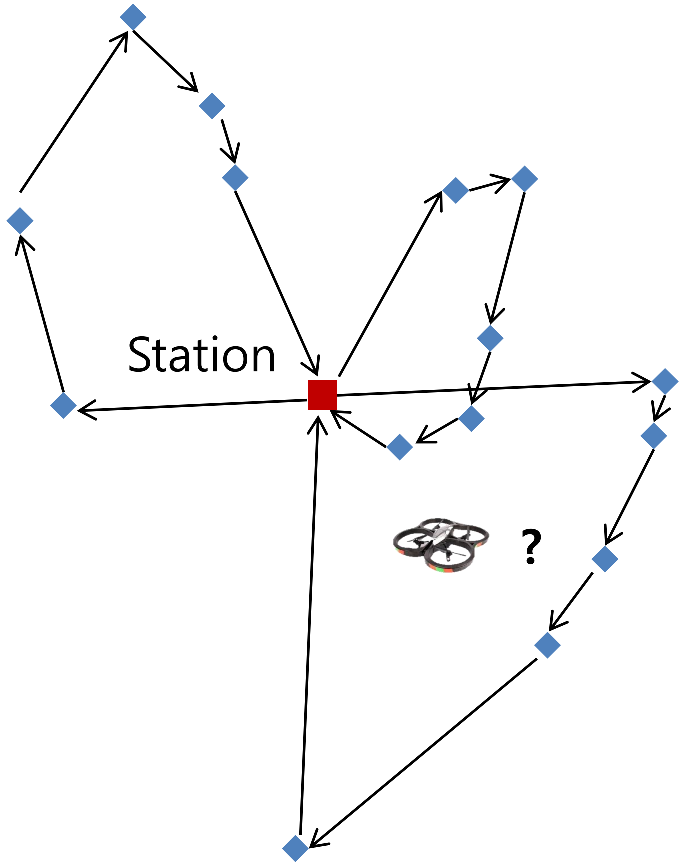
Problem description

- How much UAV do we need to provide persistent service?



Problem description

- How much UAV do we need to provide persistent service in a region?



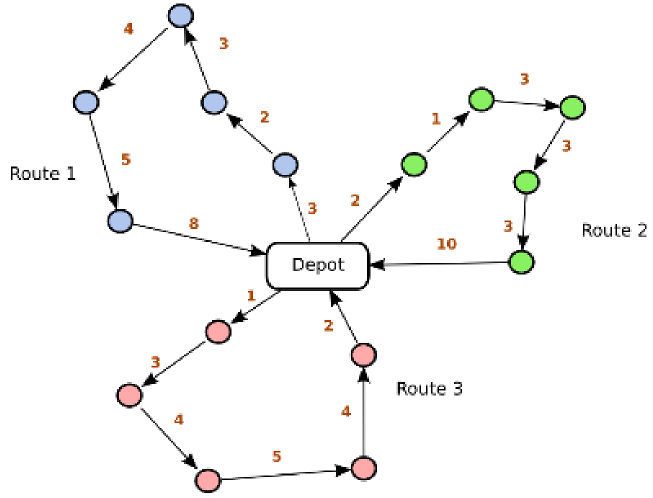
1. Generate paths

2. UAVs provide persistent service in this paths

3. Calculate resources for derived path

Problem description

- Multiple traveling salesmen problem (mTSP)
  - Every customer should be visited by one salesman
  - Every salesman should start from depot and return to depot
  - Minimize total traveling distance.



- Different point against mTSP
  - **At least 1 UAV should stay at each target point during entire service duration**
  - Different objective function (minimize number of resource)
  - Fuel constraint

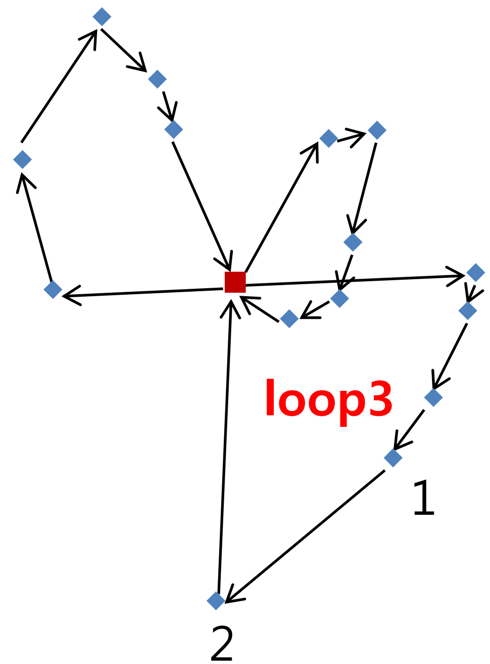
Contents

Goal of the mathematical models

- We made mathematical model to
  - Derive the minimum number of resources
  - Generate path to provide persistent service with derived number of resources
- Objective function : minimize the number of resources for persistent system

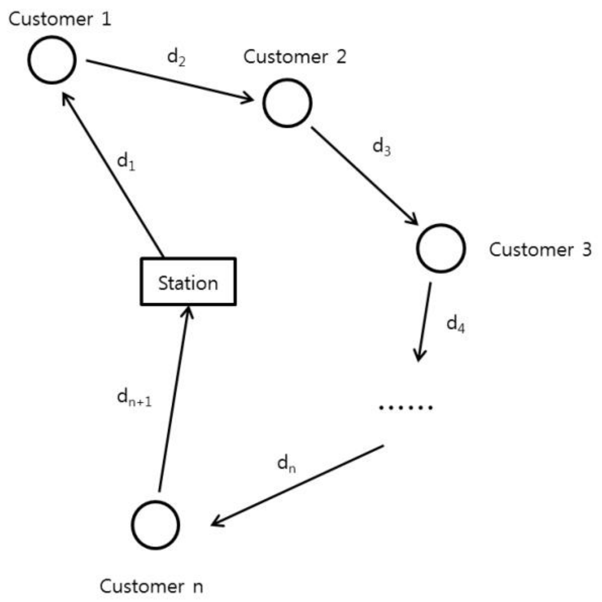
Mathematical model

- Notation
  - n : number of the customers
  - V : customer set
  - T_F:maximum flight time of the UAV
  - T_R:recharging time of the platform
  - F_S:flight speed of the UAV
  - d_{ij}:distance from customer i to customer j
  - x_{ijk} $\begin{cases} 1 : \text{if service loop k contain the arc from i to j} \\ 0 : \text{otherwise} \end{cases}$



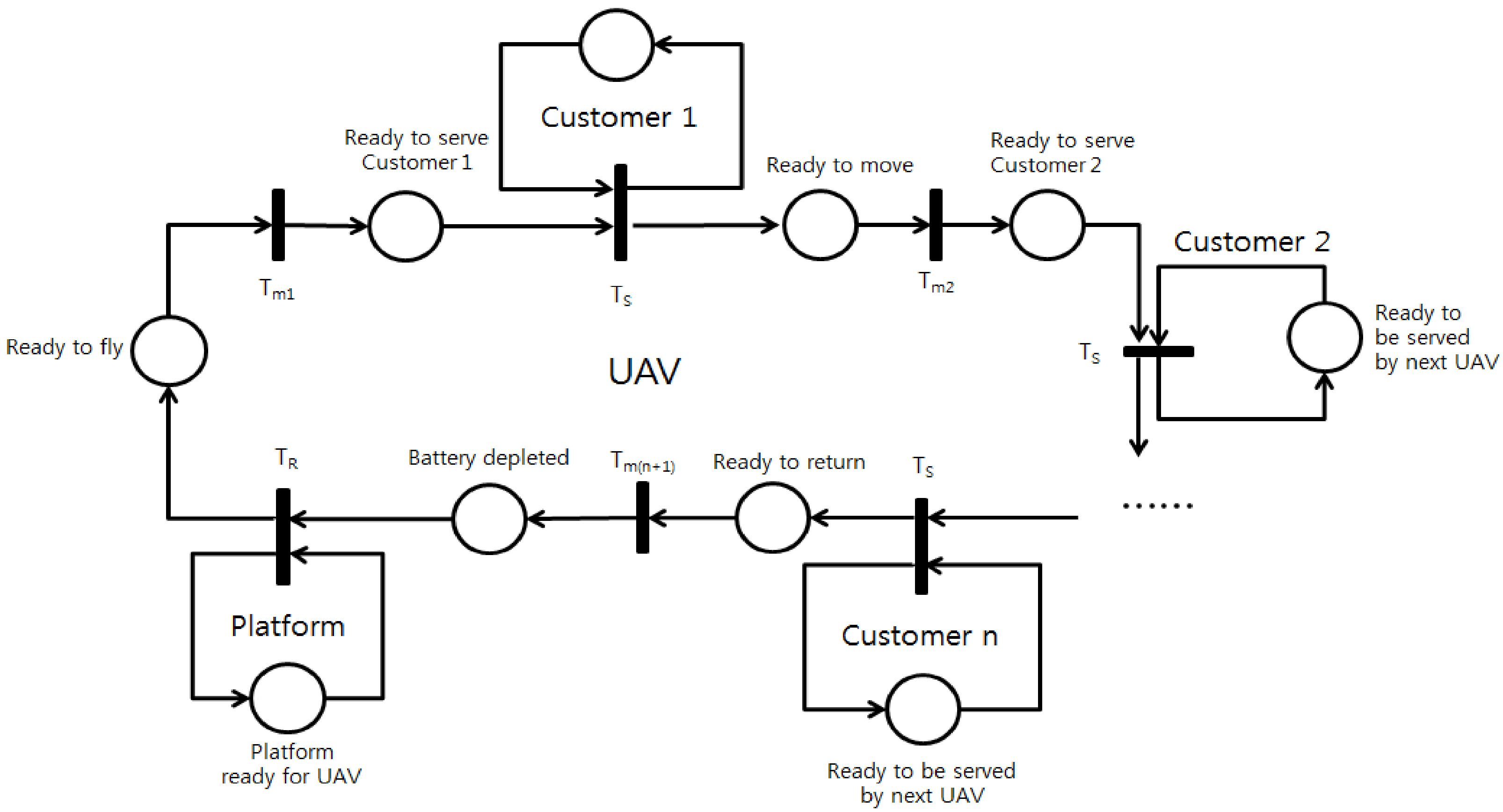
Development of objective function

- To develop the objective function
  - We use decision-free Petri net model
    - Periodicity
    - Easy to analyze
  - Petri net model is embedded into objective function



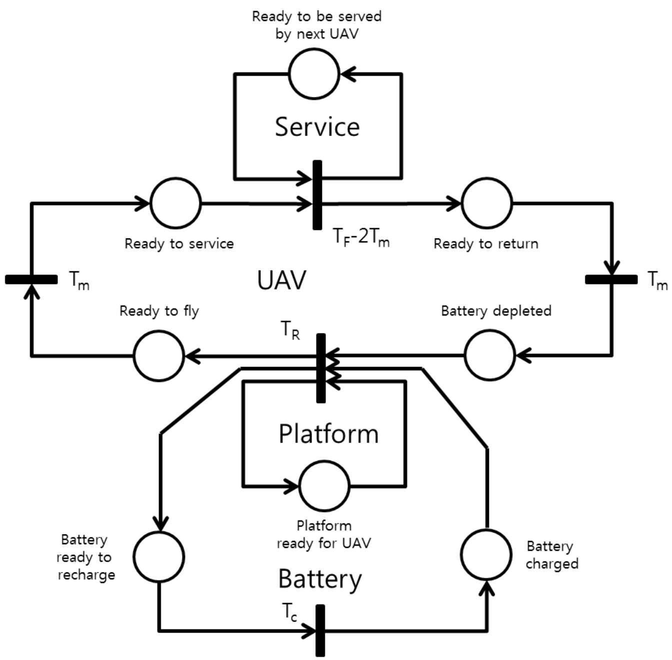
Development of objective function

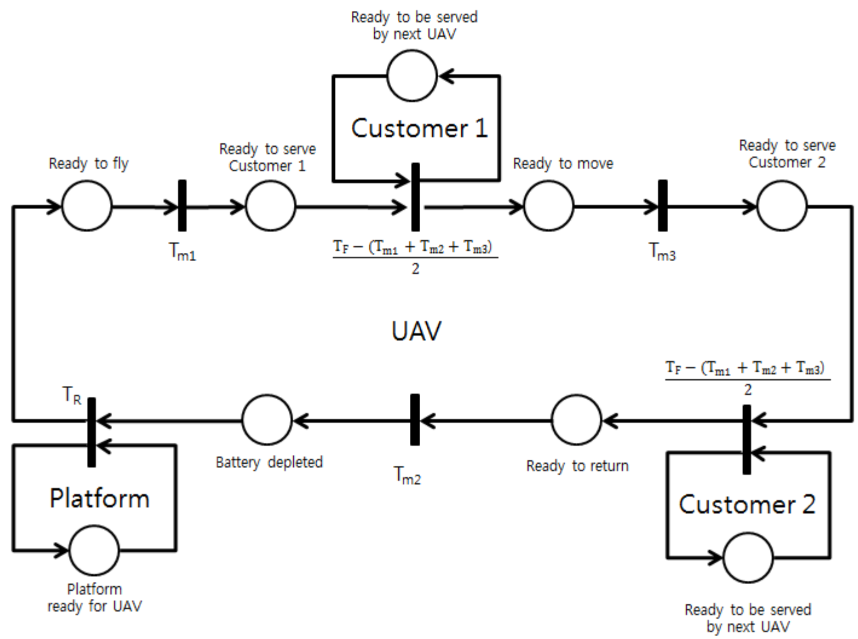
- Decision-free Petri net model of determined path



Model for 1 and 2 customers cases

- Petri net model for 1 and 2 customers cases





Proposition

- ***Proposition 1*** : The system needs minimum number of resources when all of the paths are straight.

- ***Proposition 2*** : The system needs minimum number of UAV when UAV has no unnecessary idle time.

- ***Proposition 3*** : The system needs minimum number of UAV when one UAV serve the customer.

- ***Proposition 4*** : With fixed path, minimal resources are required when each UAV visits every customer for same duration.

  – Total service time :

1	2	3	4	…	n-1	n

Development of objective function

- Service time of each customer

$$\frac{\mathrm{T_F} - (\mathrm{T_{m1}} + \mathrm{T_{m2}} + \cdots + \mathrm{T_{m(n+1)}})}{\mathrm{n}}$$

- Minimum number of resources for n customers loop

  – Number of UAV

$$\left\lceil \frac{nF_S(T_F+T_R)}{F_ST_F-(d_1+d_2+\cdots+d_{n+1})} \right\rceil \le N_{UAV}$$

  – Number of platform

$$\left\lceil \frac{nF_ST_R}{F_ST_F-(d_1+d_2+\cdots+d_{n+1})} \right\rceil \le N_{plat}$$

  – Number of battery

$$\begin{cases} \left\lceil \frac{nF_S(T_F+T_R)}{F_ST_F-(d_1+d_2+\cdots+d_{n+1})} \right\rceil \le N_{batt} & \text{(Recharging platform)} \\ \left\lceil \frac{nF_S(T_F+T_R)}{F_ST_F-(d_1+d_2+\cdots+d_{n+1})} \right\rceil + \left\lceil \frac{nF_S(T_c+T_R)}{F_ST_F-(d_1+d_2+\cdots+d_{n+1})} \right\rceil \le N_{batt} & \text{(Replacement platform)} \end{cases}$$

Mathematical model : number of UAV

$$\text{Min} \sum_{k=1}^{n} \left[\frac{\sum_{i=0}^{n} \sum_{j=0}^{n} x_{ijk} (T_F + T_R) F_S}{T_F F_S - \left(\sum_{i=0}^{n} \sum_{j=0}^{n} d_{ij} x_{ijk} \right)} \right]$$

s.t.

$$\sum_{j=0}^{n} x_{0jk} = 1 \qquad \forall k \qquad (1)$$

$$\sum_{i=0}^{n} x_{i0k} = 1 \qquad \forall k \qquad (2)$$

$$\sum_{i=0}^{n} \sum_{k=1}^{n} x_{ijk} = 1 \qquad \forall j \in V \qquad (3)$$

$$\sum_{i=0}^{n} x_{ijk} - \sum_{i=0}^{n} x_{jik} = 0 \qquad \forall j, k \qquad (4)$$

Mathematical model : number of UAV(cont.)

$$\sum_{i=0}^{n}\sum_{j=0}^{n} d_{ij}x_{ijk} \leq T_F F_S \qquad \forall k \qquad (5)$$

$$u_i - u_j + n\sum_{k=1}^{n} x_{ijk} \leq n-1 \qquad i \neq j = 1, \cdots, n \qquad (6)$$

$$x_{ijk} \in \{0,1\} \qquad \forall i,j,k \qquad (7)$$

$$u_i \quad is\ integer \qquad \forall i \qquad (8)$$

- Persistent service is embedded into objective function

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Solution approaches

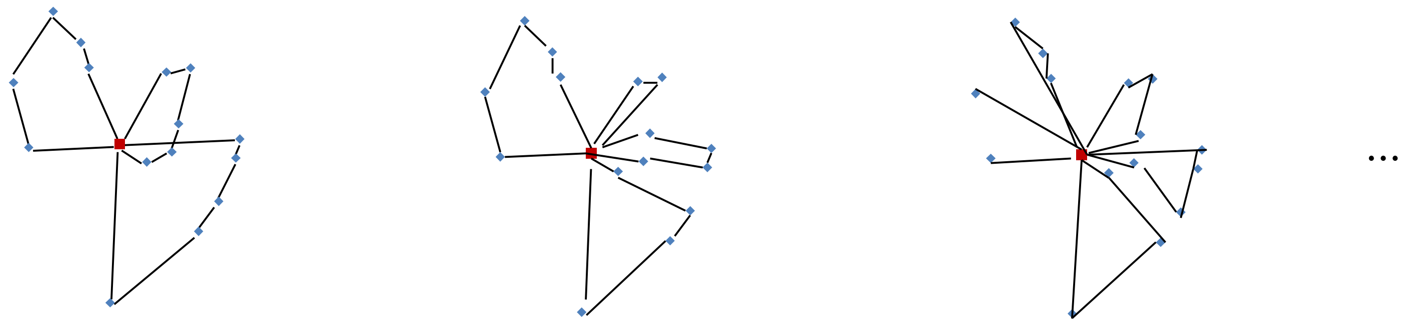
- Non-smooth objective function with integer decision variables
  - Cannot use commercial software

- Enumeration approach
  - Search all possible cases
  - Give the optimal solution
  - Computational time issue

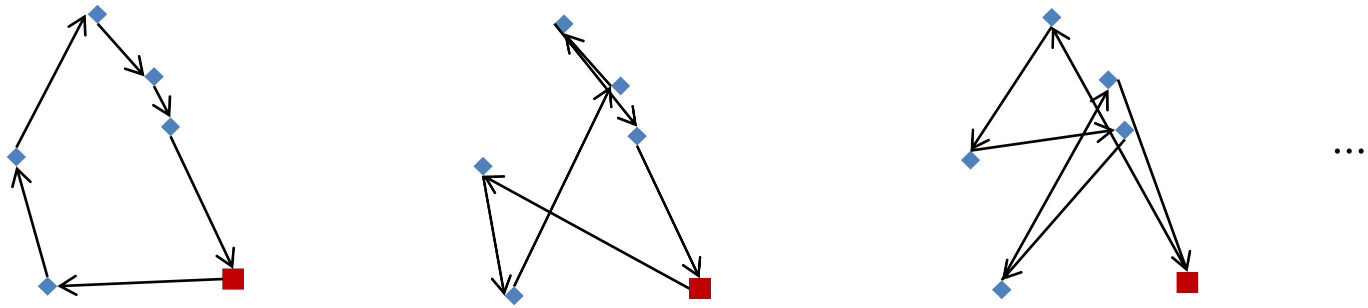
- Heuristic
  - Based on saving algorithm (Clark and Wright, 1964)
  - Give optimal or near optimal solution
  - Reasonable computation time

Solution approaches: Enumeration

- Find all possible cases
- Steps
  - 1. Set separating problem : Search all possible set of customers



  - 2. Sequence finding problem : Search all possible sequence of determined set



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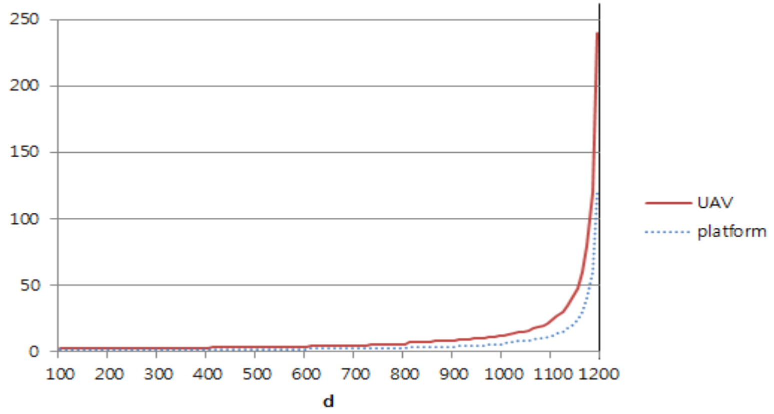
Solution approaches: Heuristic

- Relationship between distance and required number of resources

- The number of required resources is exponentially increase when the traveling distance approach to the maximum flight distance



$T_F = 600, T_R = 600, F_S = 4$, maximum flight distance = 2400)

Solution approaches: Heuristic

- Based on saving algorithm
  - Heuristic for vehicle routing problem
  - Finding minimum traveling distance(this is bad for out model)
- Add the modified distance constraint
  - At first, we use maximum flight distance for virtual limit
- Adjust virtual limit
  - Gradually reduce/increase virtual limit
  - Repeat modified saving algorithm to find best solution until the iterations reach the preset number.
  - Make the solution converge to the specific point

Solution approaches: Heuristic

- Pseudo code of the heuristic to derive number of UAV

```
Find the Euclidian distance from customer(station) i to customer(station) j (set)
Set input parameters(flight time, recharging time, flight speed)
Set best_value ← big M, p ← 1, r ← 0.1, constraint of distance D ← maximum flight distance
while current iteration is not equal to preset number of iteration do
   Calculate p+(up+down)*r
   if p>1 do
     continue;
  else
     p ← p+(up+down)*r;
     D ← D*p;
     Execute saving algorithm with constraint D and $d_{ij}$ information
  For all service loop do
     Calculate $\left\lceil \frac{nF_S(T_F+T_R)}{F_S T_F-(d_1+d_2+\cdots+d_{n+1})} \right\rceil$ as required UAV for service loop
   current total required UAV ← sum of UAV of each service loop
   Initialization of former up, and down value to 0
   if current total required UAV < best_value do
      Best_value ← current total required UAV
      Down ← 1;
   else
      Up ← 1
  r←r*0.95;
Output the minimum number of required UAV for system
```

Numerical example

- Comparison between solution approaches

Number of customers	Enumerative method		Heuristic		Objective value Gap
	Number of UAV	Computation time (sec)	Number of UAV	Computation time(sec)	
3	19	<0.05	19	<0.05	0
4	25	<0.05	25	<0.05	0
5	30	0.1	30	<0.05	0
6	36	0.1	36	<0.05	0
7	43	1.2	43	<0.05	0
8	**49**	**17**	**50**	**<0.05**	**2%**
9	**56**	**476**	**57**	**<0.05**	**1.7%**
10	**62**	**14631(>4h)**	**63**	**<0.05**	**1.6%**

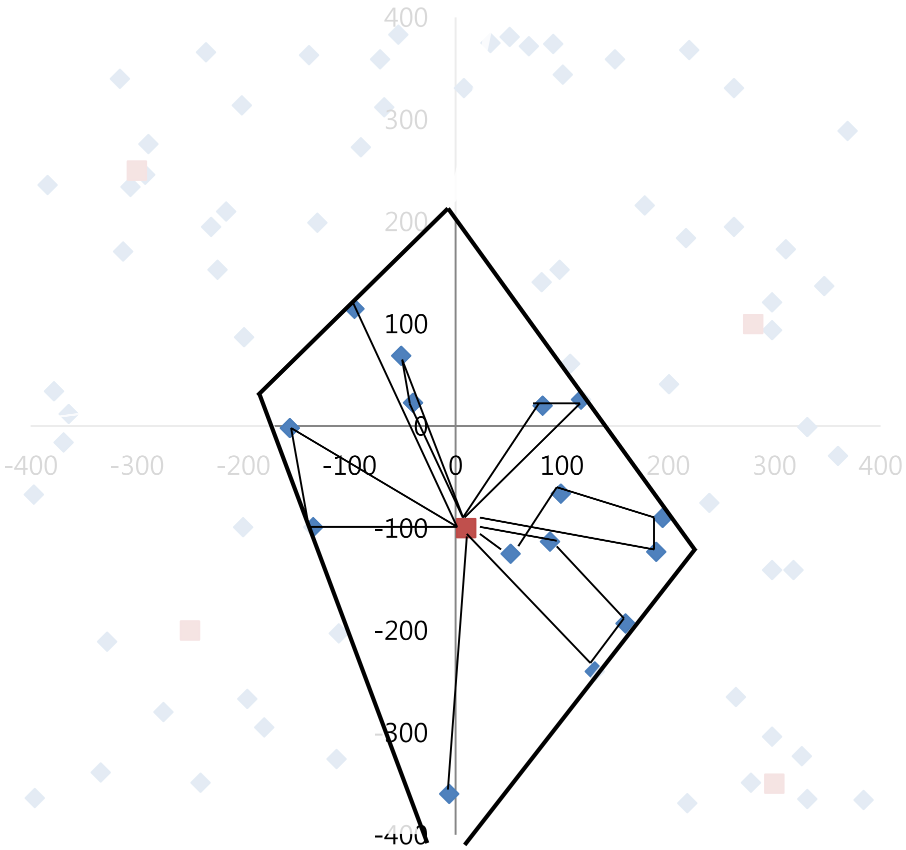
Numerical example

- Result of heuristic for large size problem

Number of customers	Enumerative method		Heuristic	
	Number of UAV	Computation time(sec)	Number of UAV	Computation time(sec)
50	-	-	309	0.4
100	-	-	622	2
200	-	-	1230	23.26
500	-	-	3085	587.86
1000	-	-	6141	15081.69

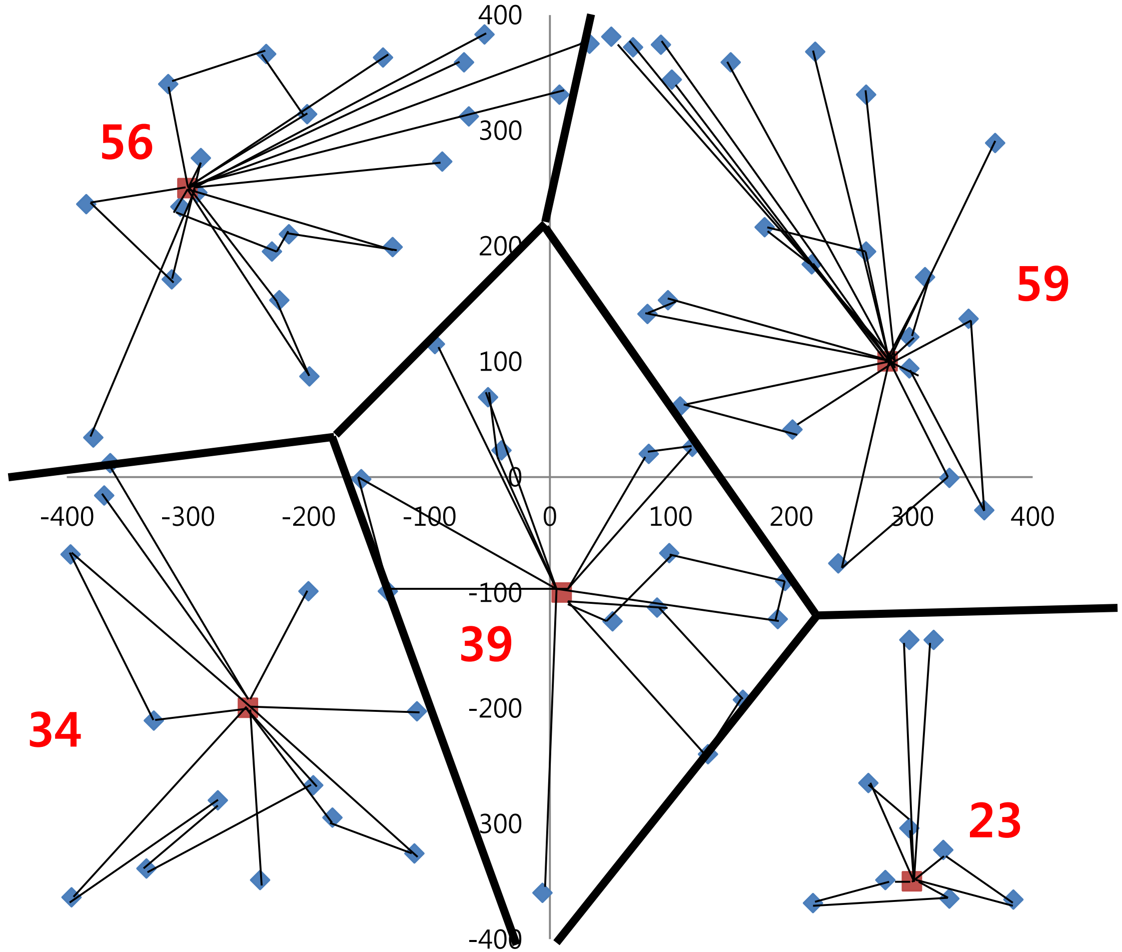
Numerical example

- How much UAV do we need to provide persistent service?
  - We need 39 UAVs to provide persistent service



Numerical example

- How much UAV do we need to provide persistent service?



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Mathematical model : multiple station

$$\text{Min} \sum_{k=1}^{n} \left[\frac{\sum_{i=1}^{n} \sum_{j=1}^{n} x_{ijk}(T_F + T_R)F_S}{T_F F_S - \left(\sum_{i=1}^{n+m} \sum_{j=1}^{n+m} d_{ij} x_{ijk}\right)} \right]$$

s.t.

$$\sum_{j=1}^{n+\mathrm{m}} x_{\mathrm{h}jk} = 1 \qquad \forall k;\ h = n+1, \cdots, n+m \qquad (1)$$

$$\sum_{i=1}^{n+\mathrm{m}} x_{i\mathrm{h}k} = 1 \qquad \forall k;\ h = n+1, \cdots, n+m \qquad (2)$$

$$\sum_{i=1}^{n+\mathrm{m}} \sum_{k=1}^{n} x_{ijk} = 1 \qquad \forall j \in V \qquad (3)$$

$$\sum_{i=1}^{n+\mathrm{m}} x_{ijk} - \sum_{i=1}^{n+\mathrm{m}} x_{jik} = 0 \qquad \forall j, k \qquad (4)$$

Mathematical model : multiple station(cont.)

$$\sum_{i=1}^{n+\mathrm{m}} \sum_{j=1}^{n+\mathrm{m}} d_{ij} x_{ijk} \le T_F F_S \qquad \forall k \qquad (5)$$

$$u_i - u_j + n \sum_{k=1}^{n} x_{ijk} \le n - 1 \qquad i \ne j = 1, \cdots, n \qquad (6)$$

$$x_{ijk} = 0 \qquad i \ne j = n+1, \cdots, n+m, \ \forall k \qquad (7)$$

$$x_{ijk} \in \{0,1\} \qquad \forall i, j, k \qquad (8)$$

$$u_i \quad is\ integer \qquad \forall i \qquad (9)$$

- *1, ⋯, n* : customer index; *n+1, ⋯, n+m* : station index

Concluding remarks

- For the commercial reason, resource analysis is needed
- Deriving the minimum number of resources and service paths
- Mathematical model is developed
- To solve the problem, enumerative method and heuristic is developed
- General mathematical model is developed
- In the future, solving method for multiple station case should be developed