Persistent UAV service: Overview

xS3D

Department of Industrial and Systems Engineering
KAIST, South Korea

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Presentation Overview

• Motivation for persistent service
• Overall orchestration of UAV service system
• UAV service system : Components and prototype
  - Central planning
  - UAV guidance system
  - Automatic replenishment station
  - System demonstration
• Concluding remarks
Motivation

• Large expensive UAVs
  – Usually military purpose
  – Operate for many hours
  – Travel long distances

• Small inexpensive UAVs
  – A lot of application area such as tracking, communication relay, environmental / fire / national boundary monitoring, cartography, disaster relief and so on.
  – Limited duration of mission
  – Limited distance

• To increase the usability of small UAVs, systems for persistent operation is required
  – Collection of UAVs, refueling stations, automatic operation system
  – Methods to orchestrate their operations (scheduling issue)
Overall orchestration of UAV service system

Random arrival of customer information

Random path and duration as customer request

Vision technology

UAV operation system

Central planning

Automatic replenishment station

Persistent UAV service

UAVs

Moving objective trajectory

Service station 1
Service station 2
Object 1
Object 2
Object 3
Service station 3
UAV 1
UAV 2
UAV 3
UAV 4
UAV 5

Vision technology

Heterogeneous UAVs

Central planning

Automatic replenishment station

Random arrival of customer information

Random path and duration as customer request

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Moving objective trajectory

UAV 1

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Overall orchestration of UAV service system

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UAV service system

Persistent UAV service

Heterogeneous UAVs

Moving objective trajectory
System description

- Persistent UAV system with distributed multiple service stations
  - Follow deterministic time-space trajectories without interruption
  - Capacitated UAVs can use any station and should return after mission
System description

Customer & UAV information

Optimization algorithm

Detail Schedule

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To follow a time-space trajectory, the trajectory is divided into pieces (split jobs).

- Objective moves
  - From point (50,250) to (950,750)
  - From 13:06 to 13:20
Mathematical Model

• Notations

\( i, j \) : Indices for jobs
\( s \) : Index for stations
\( k \) : Index for UAVs
\( r \) : Index of a UAV’s \( r^{th} \) flight
\( N_J \) : Number of split jobs
\( N_{UAV} \) : Number of UAVs in the system
\( N_{STA} \) : Number of recharge stations
\( N_R \) : Maximum number of flight per UAV during the time horizon
\( M \) : Large positive number
\( (x_s^i, y_s^i) \) : Start point of split job \( i \)
\( (x_e^i, y_e^i) \) : End point of split job \( i \)
\( D_{ij} \) : Distance from split job \( i^{th} \) finish point to split job \( j^{th} \) start point, \( D_{ij} \neq D_{ji} \)
\( E_i \) : Start time of split job \( i \)
\( P_i \) : Processing time or split job \( i \)
\( q_k \) : Maximum traveling time of UAV \( k \)
\( S_{ok} \) : Initial location(station) of UAV \( k \)
\( T S_k \) : Travel speed of UAV \( k \)
Mathematical Model

• Notation
  \[\Omega_J = \{1, \ldots, N_J\}, \text{Set of split jobs}\]
  \[\Omega_{JD} = \{1, \ldots, N_J+1\}, \text{Set of split jobs and dummy jobs}\]
  \[\Omega_{SS} = \{N_J+2, N_J+4, \ldots, N_J+2 \cdot N_{STA}\}, \text{set of UAV flight start station}\]
  \[\Omega_{SE} = \{N_J+3, N_J+5, \ldots, N_J+2 \cdot N_{STA}+1\}, \text{set of UAV flight end station}\]
  \[\Omega_A = (\Omega_{JD} U \Omega_{SS} U \Omega_{SE}) = \{1, \ldots, N_J+2 \cdot N_{STA}+1\}, \text{set of all jobs and recharge stations}\]

• Decision Variables
  \[X_{ijkr} = 1 \text{ if UAV } k \text{ processes split job } j \text{ or recharges at station } j \text{ after processing split job } i \text{ or recharging at station } i \text{ during the } r^{th} \text{ flight}; 0, \text{otherwise}\]
  \[Y_{ikr} = 1 \text{ if UAV } k \text{ processes split job } i \text{ during its } r^{th} \text{ flight}; 0, \text{otherwise.}\]
  \[C_{ikr} \text{ is job } i's \text{ start time by UAV } k \text{ during its } r^{th} \text{ flight or UAV } k's \text{ recharge start time at station } i; \text{otherwise its value is } 0.\]
Mathematical Model

• Mathematical formulation

Minimize \[ \sum_{k \in K} \sum_{r \in R} \sum_{i \in \Omega} \sum_{j \in \Omega} D_{ij} \cdot X_{ikr} \]

Subject to

\[ \sum_{j \in \Omega} X_{skr, jk1} = 1 \quad (k \in K) \]

\[ \sum_{s \in \Omega_{SE}} \sum_{j \in \Omega} X_{skr} = 1 \quad (k \in K, \ r \in R) \]

\[ \sum_{s \in \Omega_{SE}} \sum_{i \in \Omega} X_{iskr} = 1 \quad (k \in K, \ r \in R) \]

\[ \sum_{i \in \Omega} X_{iskr} = \sum_{i \in \Omega} X_{s-1,ikr+1} \quad (k \in K, \ r = 1 \ldots N_R - 1, s \in \Omega_{SE}) \]

\[ C_{skr} = C_{s-1,kr+1} \quad (k \in K, \ r = 1 \ldots N_R - 1, s \in \Omega_{SE}) \]

\[ \sum_{k \in K} \sum_{r \in R} \sum_{i \in \Omega} \sum_{j \in \Omega} X_{ijk} = 1 \quad (j \in \Omega_j) \]

\[ \sum_{j \in \Omega} X_{ijk} - \sum_{j \in \Omega} X_{jikr} = 0 \quad (i \in \Omega_j, k \in K, \ r \in R) \]

\[ \sum_{i \in \Omega} X_{iskr} = 0 \quad (k \in K, \ r \in R, s \in \Omega_{SS}) \]
Mathematical Model

- Mathematical formulation

\[ C_{ikr} + P_i + D_{ij} / TS_k - C_{jkr} \leq M (1 - X_{ijk}) \quad (i \in \Omega_{JD} \cup \Omega_{SS}, j \in \Omega_{JD} \cup \Omega_{SE}, k \in K, r \in R) \]

\[ \sum_{j \in \Omega_{JD} \cup \Omega_{SE}} X_{ijk} \geq Y_{ikr} \quad (i \in \Omega_J, k \in K, r \in R) \]

\[ M \cdot Y_{ikr} \geq C_{ikr} \quad (i \in \Omega_J, k \in K, r \in R) \]

\[ \sum_{k \in K} \sum_{r \in R} C_{ikr} = E_i \quad (i \in \Omega_J) \]

\[ \sum_{i \in \Omega_A} \sum_{j \in \Omega_A} D_{ij} / TS_k \cdot X_{ijk} + \sum_{i \in \Omega_{JD}} \sum_{j \in \Omega_{SS}} P_i \cdot X_{ijk} \leq q_k \quad (k \in K, r \in R) \]

\[ X_{sdr} = X_{d,r+1,kr} \quad (k \in K, r \in R, s \in \Omega_{SS}) \]

\[ X_{dikr} + X_{idkr} = 0 \quad (k \in K, r \in R, i \in \Omega_J) \]

\[ C_{ikr} \geq 0 \quad (k \in K, r \in R, i \in \Omega_A) \]

\[ X_{ijk} \in \{0,1\} \quad (k \in K, r \in R, i \in \Omega_A, j \in \Omega_A) \]

\[ Y_{ikr} \in \{0,1\} \quad (k \in K, r \in R, i \in \Omega_A) \]
UAV guidance system

< AR drone 2.0 >

1280 × 720 pixel front camera

320×240 pixel belly camera

< WIFI >

< Ipad 3>

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UAV guidance system

Roles of UAV guidance system

1. Receive and implement the schedule from the MILP.

2. Convert the video from the UAV cameras into usable information for directing the motion of the UAVs

3. Enable a human overseer to monitor the UAV progress via video and adjust feedback control gain values for various situations

4. Allows for a human overseer to initiate emergency actions such as immediate landing.
1. The color video from the camera is acquired via TCP port and processed using OpenCV framework.

2. The image is separated into three RGB channels. These three images are used to determine the color of the targeted image.

3. Control inputs including the longitudinal-lateral tilt angles, height and yaw angular velocity are calculated from the number and mean coordinate of target pixels in the processed image.
Automatic replenishment station

- Each AR Drone 2.0 uses a three cell lithium polymer battery
- Four copper leads (three for each terminal and one for the ground terminal) were threaded from the battery inside the UAV to the four feet of the drone
- The service station consists of four pads, one for each foot of the drone.
- Each such pad connects to the UAV battery via the leads on the drone feet
System demonstration
System demonstration

Demonstration description

< Demonstration layout >

< Schedule by MILP >

<table>
<thead>
<tr>
<th>UAV</th>
<th>Start station</th>
<th>Assigned job</th>
<th>End station</th>
<th>Service start time</th>
<th>Service end time</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>1,2,3,4</td>
<td>2</td>
<td>2</td>
<td>10</td>
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<tr>
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<td>2</td>
<td>5,6,7,8</td>
<td>3</td>
<td>10</td>
<td>18</td>
</tr>
</tbody>
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Experiments

- Demonstration video
Concluding remarks

- To increase the usability of small UAVs, prototype systems for persistent operation is developed.

- As a components of persistent UAV service system, MILP for deriving UAV schedules, UAV guidance system, automatic replenishment station were suggested.

- MILP generates UAV schedules using customer information and system resource information such as location of station and number & location of UAVs.

- UAV guidance system provides uninterrupted customer tracking service by using vision technology.

- Demonstration shows the orchestration of those system components and applicability of proposed UAV service system.
Literature Review

• **Scheduling methods without a distance or time restriction**

• **Scheduling methods for limited flight duration**

• **Scheduling method for persistent UAV operation**

• **Battery recharge/exchange methods**