Energy-efficient Trajectory Planning and Speed Scheduling for UAV-assisted Data Collection

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Outline

- Background
- Problem Formulation
- Solutions
- Simulation
- Conclusion
UAV-assisted Data Collection Scenario

A UAV collects data from ground sensors (GSs) deployed in an open area.

UAV-mounted BS

GS 1

GS 2

GS 3

GS 4
Motivation

- Key issues: Limited on-board energy for UAV
- Flight power occupies nearly 1000 times than that of communication power

We focus on minimizing propulsion energy of UAV
Motivation

• Most work does not consider a fine-grained energy consumption model

• Most of them only consider a distance-related model or duration-related energy consumption models
A sophisticated energy model

\[ E(q(t)) = \int_0^T \left[ c_1 ||v(t)||^3 + \frac{c_2}{||v(t)||} (1 + \frac{||a(t)||^2 - (a^T(t)v(t))^2}{g^2}) \right] dt \]

Challenges to our problem

1. Minimizing flight energy to collect all data
   - **Slow speed**
     - Sufficient time to collect data
     - Cost more flight energy
   - **Faster speed**
     - Less time to collect data
     - Save more flight energy

   Best trade-off must be found

2. Trajectory & speed must be considered together
   - Longer trajectory may save energy
   - Lower speed may consume more energy

   Proper trajectory and speed design must be found
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GSs and UAV

- $m$ Ground Sensors (GSs), 1 UAV
- The UAV collects data from GSs when flying in communication range of them

We aim to minimizing UAV’s energy consumption by finding a proper trajectory and flight speed, under constraints of data collection and UAV’s trajectory
Transmission range and required time

- GS has a transmission range \((b_i, d_i)\)
- Within range, GS \(i\) requires \(t_i\) time to upload data
- We allow the transmission ranges of GSs are different but they must be adjacent

\[
0 = b_1 < b_2 < b_3 < \cdots < b_m \quad d_1 < d_2 < d_3 < \cdots < d_m
\]

Key points \(D = b \cup d = \{b_1, \ldots, b_m, d_1, \ldots d_m\}\)
Trajectory

• Key points D divide the trajectory into $2m+1$ parts:

$$L = \{L_1, L_2, \ldots, L_n\}$$

• Length of curve $L_i$ is $l_i$, denoted as:

$$l_i = \int_{L_{i-1}}^{L_i} dl$$
Distance / location constraint

• Length of trajectory between two key points must be larger than their straight distance

\[ \int_{L(D_i, D_{i+1})} dl \geq dis(D_i, D_{i+1}). \]

• All key points must be located on the range circle of each sensor

\[ dis(b_i, SN_i) = dis(d_i, SN_i) = Cr_i, \ i \in \{1, 2, ..., m\} \]
Service time/Deadline constraint

- Service time constraint

\[ \int_{L(b_i,d_i)} \frac{dl}{v(l)} \geq t_i, i \in \{1, 2, \ldots, m\} \]

- Deadline constraint

\[ \int_{L(b_1,d_m)} \frac{dl}{v(l)} \leq T. \]
ETPSS problem

- ETPSS problem: Find the proper speed and trajectory to
  1. minimize UAV energy consumption
  2. satisfy distance / location constraint
  3. satisfy service time / deadline constraint
Framework for ETSO solution

Step 1: Initialize trajectory

Step 2: Schedule flight speed

Step 3: Adjust flight length
Step 1: Initialize trajectory

• Construct the initial graph

\[ G = (V, E) \]

\[ V = M \cup \{u\} \]  

Vertexes: airport and all key points

\[ e_{ij} \in E, \{i, j\} \in M \]  

Edges: lines between two neighboring vertexes

• Use travelling salesman problem (TSP) to initialize the trajectory
Step 1: Initialize trajectory

1. Input GS and UAV’s location
2. Construct the initial graph
3. Solve the TSP problem by using SA algorithm
4. Output initial trajectory L
Step 2: Schedule flight speed

• Construct a time-distance diagram

• Satisfying service time / deadline constraints

  • $T(l)$: Service time constraints
  
  • $F(l)$: Deadline constraints
  
  • $L(l)$: Optimal curve whose slope is reciprocal of speed
Step 2: Schedule flight speed

Theorem 1: UAV flying in a constant speed consumes less energy than flying in a changing speed.
Step 2: Schedule flight speed

Theorem 2: Optimal curve property

- $L(l)$ must intersect with corner of upper bound $T(l)$ or lower bound $F(l)$
- Assume in point $d_i$, we have $L(d_i) = T(d_i)$, the slope change must be negative
- Assume in point $b_i$, we have $L(b_i) = T(b_i)$, the slope change must be positive
Step 2: Schedule flight speed

- Input initial trajectory $L$
- All GSs have been served?
  - Yes
  - No
  - Connect all corners of $T(l)$ and $F(l)$
  - Find the very last feasible solution

End
Step 2: Schedule flight speed

Step 1

Step 2

Step 3
Step 3: Adjust flight length

Input flight speed and flight time for trajectory $L_i$

All trajectories been adjusted?

Yes

No

Calculate the min-energy flight distance $L_i^*$

$L_i^* < \text{Dis}(D_i, D_{i+1})$?

Yes

Update $L_i = \text{Dis}(D_i, D_{i+1})$

No

Update $L_i = L_i^*$

End
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Simulation parameters

- GSs are randomly deployed in 2km×2km area
- We evaluate propulsion energy consumption of UAV with compared algorithms

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t_i$</td>
<td>[0.5, 2]s</td>
<td>Service time for $SN_i$</td>
</tr>
<tr>
<td>$m$</td>
<td>[10, 1000]</td>
<td>Number of GSs</td>
</tr>
<tr>
<td>$v$</td>
<td>[5, 1000]</td>
<td>Flight speed of UAV</td>
</tr>
<tr>
<td>$H$</td>
<td>100m</td>
<td>Flight altitude of UAV</td>
</tr>
<tr>
<td>$c_1$</td>
<td>$9.26 \times 10^{-4}$</td>
<td>Parameter of energy model</td>
</tr>
<tr>
<td>$c_2$</td>
<td>2250</td>
<td>Parameter of energy model</td>
</tr>
<tr>
<td>$Cr$</td>
<td>[30, 50]m</td>
<td>Communication range for GSs</td>
</tr>
</tbody>
</table>
Compared algorithms

• Task Completion Speed (TCS): UAV reaches departing key point $d_i$ at time $t = \sum_{j=1}^{i} t_j$

• NoTAA: The ETSO scheme without Algorithm TAA

• TAA-ALG: The UAV flies along the trajectory worked out by TAA and speed scheduling algorithm using online Algorithm ALG proposed in previous work
Simulation Results

Our proposed algorithm ETSO costs less propulsion energy consumption than compared algorithms.
Simulation Results

![Graph showing the impact of GS number on average flight speed.](image)

**Fig. 9:** The impact of GS number on average flight speed

Flight speed in Algorithm ETSO are more stable than that of compared algorithms
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Conclusion

- We investigate a UAV data collection problem from GSs deployed in an open area.

- We use a sophisticated energy consumption model to illustrate propulsion consumption of UAV.

- We propose a three-step algorithm to jointly design trajectory and schedule flight speed for UAV, in which the second step is proved to be an optimal offline algorithm.

- Simulation results show that our algorithm preforms well in energy-efficiency.
Thank You!

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