Agent-based Formation Flight Coalition under Incomplete Information

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Outline

1. Background
2. Formulation
3. MAS coalition
4. Simulation results and conclusions
5. Future Works
1 Background

1.1 Why formation flight?

**ACI:** Air traffic flow, fuel consumption, and CO2 emissions are expected to be doubled in 2020.

**Lisbon 2020 Vision:** The CO2 emissions shall be decreased by 50% of 2005 in 2050.

**CAAC:** The CO2 emissions shall be cut down to 40-45% of 2005 in 2020.
1.2 What is formation light?

—*Pilot’s Manual for Basic Flying Training, Royal Canadian Air Force*  
**TC-44, 1962**

Two or more aircraft traveling and maneuvering together in a disciplined, synchronized, and predetermined manner.

—*RVSM SEPARATION FOR RVSM COMPLIANT AIRCRAFT OPERATING IN FORMATION FLIGHTS, ICAO, 2005*

Formation flight is defined as more than one aircraft operating as a single aircraft with regard to navigation and position reporting.
1. Background

1.3 Potential benefits of formation flight

- **Reduce fuel consumptions**

  Lissaman (1970): 71% greater range can be achieved for 25 birds flying in formation

- **Nehrbass (2004)**
  Transatlantic point to point commercial formation flight, 32.2% fuel reduction

- **Ning (2011)**
  26-31% reduction of induced drag for a 2-aircraft formation and 38-45% for 3-aircraft formation

- **Xue (2012)**
  1.2 billion dollars can be achieved via formation flight in NAS each year
1. Background

1. 4 Potential benefits of formation flight


1 Background

1.5 Is formation flight feasible in commercial aviation?

- Airbus carried out a formation flying trial using two A380 airplanes in 2013 in Australia.
- Dijkers H P A, Van Nunen R, Bos D, et al. (2011) Preliminary aircraft design, e.g., low wing, engine installation to give a more idealized wake effects
1 Background

1. 6 Problems of formation flight

I. Aerodynamic coupled effects [4-13]
II. Precision wake detection and estimation [14-17]
III. Peak-seeking control based on drag reduction [18-20]
IV. Formation flight path planning [9-13, 21-23]

Delft University of Technology
1 Background

1. 6 Problems of formation flight

I. Which of flights have the most probability to fly in formation approximately?

II. What is the exact schedule of flying in formation for a feasible candidate flight set?

III. How to construct a formation

Weighted Geodesic Steiner Minimum Tree, WGSMT

I. Weighted Geodesic Steiner Minimum Tree, WGSMT

Formation pattern recognition

Formation coalition

Formation path planning

• Maximum fuel efficiency
2 Formulation

2. 1 Description of formation coalition

- **When, Where and with Who**
  
  I. flights are planned to join and break away from a formation, with the objective of maximizing the overall fuel savings.
  
  II. It is interpreted as a recursive construction of weighted geodesic Steiner Minimum Tree (WGSMT)
2. 2 Challenges

1. **NP hard**

   **Coalition** — multistage and decentralized negotiation to form a coalition.

   **Path planning on sphere** — To evaluate the utility of a specific formation coalition, the formation path shall be constructed via solving a sequential WGSMT trees. However there is no analytical solution to WGSMT, therefore a numerical WGSMT solution algorithm is needed.
2 Motivation

2.2 Challenges

II. Incomplete information

The minimum acceptable utility an airline would accept and the strategy an airline takes are unknown to other airlines in commercial aviation when it selects a partner to form a formation coalition. Therefore the coalition negotiation process is based on incomplete information.
A decentralized coalition problem based on MAS framework. For any agent $i$, representing a candidate flight/fleet, will select a partner $j$ to form a formation coalition $<i, j>$ based on both sides’ utility type $(e_i, e_j)$ and strategy type $(\pi_i, \pi_j)$.

Objective: to maximize both sides’ utility based on their strategy type.

Both sides’ utility not less than their minimum expected utility in $<i, j>$.

Maximum formation size satisfying Lyapunov asymptotic stability.
2 Formulation

2. 3 Formulation

Maximum formation size based on Lyapunov asymptotic stability

<table>
<thead>
<tr>
<th>Leader’s speed (kt)</th>
<th>Maneuvering radius (km)</th>
<th>Longitudinal spacing (XX spans)</th>
<th>Maximum formation size</th>
</tr>
</thead>
<tbody>
<tr>
<td>210</td>
<td>5.19</td>
<td>20</td>
<td>7</td>
</tr>
<tr>
<td>250</td>
<td>7.22</td>
<td>20</td>
<td>7</td>
</tr>
<tr>
<td>300</td>
<td>10.56</td>
<td>20</td>
<td>7</td>
</tr>
<tr>
<td>350</td>
<td>14.26</td>
<td>20</td>
<td>6</td>
</tr>
<tr>
<td>400</td>
<td>18.52</td>
<td>20</td>
<td>5</td>
</tr>
<tr>
<td>444</td>
<td>22.96</td>
<td>20</td>
<td>4</td>
</tr>
<tr>
<td>450</td>
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<tr>
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<td>33.52</td>
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<td>1</td>
</tr>
<tr>
<td>504</td>
<td>34.08</td>
<td>20</td>
<td>1</td>
</tr>
</tbody>
</table>
Both $e_j$ and $\pi_j$ are unknown to agent $i$, therefore $i$ can only use the prior distribution of $e_j$ and $\pi_j$ to choose a partner in the beginning of negotiation and revise its expectations of other agent’s unknown information through observing the outcomes of coalition negotiation in each MAS evolving generation.

\[
\max_{j \in Y(k)} \left[ \pi_i \left(1 - \pi_j \right) q_i(k)e_i^{ij}(k) + \left(1 - \pi_i \right) \pi_j(k)q_j(k)e_j^{ij}(k) \right]
\]

\[
\begin{align*}
&u_i^{ij}(k) \geq e_i D_k(o_i, g_i) \\
&u_j^{ij}(k) \geq e_j (o_j, g_j)
\end{align*}
\]

\[
\begin{align*}
&q_i(k) \leq q_{\text{max}} \\
&q_j(k) \leq q_{\text{max}}
\end{align*}
\]
2. Our considerations for the problem solving

1. The problem is solved in a decentralized way and formulated as a recursive coalition game under incomplete information.

2. A flight/fleet is modeled as an agent and created according OD pairs along with some other characteristics in each generation.

3. Agents form formations/coalitions recursively via negotiation, role assuming and state updates under incomplete information.

4. Agents revises their beliefs under incomplete information by observing the outcomes of negotiations in each generation.
3 MAS Coalition

3.1 Basic framework

**MAS model**
Build a basic framework for airlines to negotiate for coalition and to update the social organization of flights/fleets among coalitions at the end of each MAS evolving generation.

**Agent model**
Model a flight/fleet based on BDI (Belief, Desire, Intention) agent to capture the characteristics of airlines’ social behaviors and mental statuses in the process of negotiating for coalition.

**Negotiation algorithm**
Develop an algorithm for agents to negotiate for coalition based on Bayesian approach.
3 MAS Coalition

3.2 MAS model

BDI Agents

Agent  
Agent  
Agent  
Agent  

Agent formation coalition

BDI calculate  
Negotiation  
Belief update  
Role assuming  
State update  

World States

Agents’ current states  
Agents’ goal-reachable states  
Agents’ resources  
Agents’ social relationships  

Agents’ goal-reachable states  

Belief update  

Role assuming  

State update  

Negotiation  

BDI calculate  

Agent formation coalition  

World States  

Agents’ current states  

BDI Agents  

3 MAS Coalition
3 MAS Coalition

3.3 MAS Evolutionary

Agent

- Declare “Quit”
  - Yes
    - Quit criterion?
    - Negotiating to form a coalition
      - elite / everyman
      - BDI agent
        - Flight plans or coalitions
  - No
    - All agents quit?
      - role assuming state updating
      - Agents differentiation
      - Create BDI agents

Arbitrary Agent

- Declare “MAS End”
  - Yes
    - No
  - No
    - Yes
      - Quit criterion?
3 MAS Coalition

3.4 Agent model

Public properties
- Current states
- Goal-reachable states
- Fleet size
- Social class

Private properties
- Own Utility type
- Own strategy type
- Expectations of other agents’ unknown information
  - Belief set
  - Desire set
  - Intention

Known to all agents

Protected properties
- Messages

Each room only known to an authorized agent

Events
- Fail
- Omit

Predefined events during negotiation

Methods
- Belief calculation
- Desire Calculation
- Intention Calculation
- Send message
- Handle message
- Handle events
- Role assuming
- Update States

Agent’s capabilities

Only known to self

Each room only known to an authorized agent
3 MAS Coalition

3.5 Negotiation

Social rules, the basic distributions of unknown information, all agents' current states and goal reachable states, etc.

World State

Belief calculating
Belief

Desire calculating
Desire

Intention calculating
Intention

Agent's utilities in all possible coalitions
BeliefSet

All coalitions with Bayese rationality in BeliefSet
DesireSet

Choosing the best partner in DesireSet
Intention

Belief updating based on Bayesian approach
Belief Updation

Formation coalition event, e.g., fail or omit, occurring
Event

Negotiating to form a coalition
Negotiation

BDI calculation

Negotiation process
1. **Improvements of current agent model compared to previous agent model**

- Agent is developed based on BDI framework
  - More accurate description and calculation of agent’s mental states

- Negotiation is conducted between any two agents no matter what are their social classes. The social class level only affects their behaviors in negotiation and their roles in coalitions
  - Fast convergent rate of MAS
  - Better global optimality
II. Comparisons

Formation size: 3.73
Standard variation: 2.11

Formation size: 5.15
Standard variation: 1.55

- An apparent hierarchical structure of formation paths is more faithful to the operational mechanism of formation flight and indicates a more accurate mental calculation.
- A larger formation size indicates a better utility could be achieved by BDI agent model.
- A smaller standard variation indicates more fair utility split among agents.
II. Comparisons

- A faster convergence rate of MAS, i.e., 10 to 4.
- A narrower color spectrum indicates a more precision Bayesian estimation.
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Agents' expectations of other agents' utility type belonging to $e^h$

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Convergent at $k=10$

Agents' expectations of other agents' strategy type belonging to $\pi^c$

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II. Comparisons

Convergent at $k=10$

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- A faster convergence rate of MAS, i.e., 10 to 4.
- A narrower color spectrum indicates a more precision Bayesian estimation.
5 Future works

I. Uncertainties in aerodynamically coupled effects of extended formation flight shall be considered.

II. Heterogeneous aircraft performance should be involved into the model to make sure more accurate utility calculation.

III. Improving the accuracy of numerical WGSMT solution and reducing the complexity of numerical WGSMT solution algorithm are needed nowadays.

IV. The step size of belief update should be improved and well-founded through more trials.
Questions and answers!