Multi-Objective Path Planning for a Team of Unmanned Aerial Vehicles (UAVs) in a Dynamic and Uncertain Environment

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19th International Command and Control Research and Technology Symposium
June 16th-19th, 2014, Alexandria, Virginia, USA
Multi-Objective Path Planning for a Team of Unmanned Aerial Vehicles (UAVs) in a Dynamic and Uncertain Environment (BRIEFING CHARTS)
Outline

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Introduction: UAV Mission Planning

• UAVs have **ultra long endurance** and can accept **high mission risk**; these attributes make them suitable for **dull, dirty, and dangerous** tasks in complex environments:

  - **Military**:
    - Intelligence, Surveillance & Reconnaissance (ISR)
    - Search and Rescue Operations (SAR)
    - Demining Operations

  - **Security**:
    - Border Patrol
    - Surveillance of Smuggling Operations
    - Interdiction Operations

  - **Civil**:
    - Disaster Management
    - Forest Fire Detection
    - Traffic Monitoring

• In the future, UAVs are expected to operate with a higher level of autonomy to carry out complex tasks, while efficiently coordinating with unmanned ground and unmanned underwater vehicles ⇒ **Need for systematic mission planning processes**
Technical Challenges

- Lack of see and avoid capability:
  - May lead to mid-air collisions with manned vehicles
  - Restricts UAVs to operate in segregated regions in the airspace
  - Needs substantial human supervision
  - Limits operational flexibility

Flying UAV within national borders in controlled, segregated airspace over an unpopulated area

- Limited sensor ranges and payload capacity requires multiple UAVs to:
  - Work cooperatively
  - Expedite the mission execution
  - Reduce the possibility of mission failure
Hierarchical Architecture for UAV Mission Planning

- Systematic mission planning structure for conducting complex tasks involving multiple UAVs

Mission
- **Military**: Weapon delivery, ISR
- **Security**: Counter-terrorism, SAR
- **Civil**: Forest fire detection

Prior Intel

Environmental Constraints
- Weather
- Terrain
- Obstacles

Mission Environment

Asset Task

Status/Situational Awareness

Cooperative Mission Planning for Multiple UAVs

Cooperative Trajectories with Coordinated Guidance

Mission Execution

Dynamic Mission Environment

Dynamic Path Planning

Target Search & Tracking

Dynamic Task Assignment

Formation Hold

Individual Controller for UAV

Individual Controller for UAV

Reference Trajectory

Velocity/Position

Multi-Objective Path Planning for UAVs

**Objective:** *Coordinated* multi-objective path planning for a group of UAVs in a dynamic environment to carry out *time-critical mission tasks*:

- Minimize mission risk (path cost, e.g., distance of UAV from obstacle)
- Minimize task latencies

**Mission Scenario**

**Given:**
- Dynamic environment with static and dynamic obstacles, e.g., high rise buildings, manned aircraft
- Task locations, deadlines, task requirements

**Constraints:**
- Motion constraints
- Network flow constraints
- Task start time
- Synchronization

**Time Horizon**

**Task Deadlines**

**Task Requirements**

**Start Base**

**End Base**

**Start**

**End**

**Feasible paths**

**Path nodes**

**Path**

**Dynamic Obstacles**

**Static Obstacles**

**UAV**

**Task Locations**
**UAV Path Planning Formulation**

- **Multi-Objective Mixed Integer Linear Programming (MILP) Problem:**
  - **Objective I: Minimize cumulative path risk** - Time varying travel and usage cost

  \[
  \text{Obj}_1 : \min \sum_{t=0}^{T} \sum_{k=1}^{K} \sum_{(i,j) \in \Omega} r_{ijkt} x_{ijkt} \\
  x_{ijkt} = \begin{cases} 
    1, & \text{if UAV } k \text{ moves from cell } i \text{ to cell } j \text{ at time } t \\
    0, & \text{otherwise}
  \end{cases}
  \]

  where \( T \) is the time horizon, \( K \) is the total number of UAVs and \( \Omega \) is the set of accessible paths

  \( r_{ijkt} \) is the path risk experienced by UAV \( k \) in moving from cell \( i \) to cell \( j \) at time \( t \)

- **Objective II: Minimize task latency** - Delay in meeting the task deadline

  \[
  \text{Obj}_2 : \min \sum_{l=1}^{L} t_{l}^{\text{latency}}, \quad t_{l}^{\text{latency}} = \max(0, t_{l}^{\text{start}} + t_{l}^{\text{process}} - t_{l}^{\text{deadline}})
  \]

  where

  \( t_{l}^{\text{start}}, t_{l}^{\text{process}}, t_{l}^{\text{deadline}} \) denote the start time, processing time and deadline for task \( l \)

  \( L \) denotes the total number of tasks

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**Mission Area Risk Map**

- Obstacles
- Risk intensity
- Task Locations
- UAV
- Fuel Efficient Shortest Path
- Safe Path with Task Delay
- Conflicting Objectives
Multi-Objective MILP Problem Constraints

- **Network Flow Constraints**: Time-varying travel and usage cost

\[
\begin{align*}
\sum_{t=1}^{T} \sum_{i \in Q(l,t)} x_{iikt} &= 1, \forall k & 1(a) \\
\sum_{t=1}^{T} \sum_{i \in P(N,t)} x_{i^\text{in}kt} &= 1, \forall k & 1(b) \\
\sum_{t=1}^{T} \sum_{j \in Q(i,t)} x_{ijkt} &= \sum_{t=1}^{T} \sum_{j \in P(i,t)} x_{jikt} = 0, \forall k, \forall i \neq 1 \& i \neq N & 1(c) \\
\sum_{t=1}^{T} \sum_{j \in Q(i,t)} x_{ijkt} \leq \sum_{t=1}^{T} \sum_{j \in P(i,t)} x_{jikt}, & \forall k, \forall i \neq 1, \forall \tilde{T} < T & 1(d)
\end{align*}
\]

where

- \( x_{ijkt} \): Path risk
- \( k \): UAV index
- \( N \): Total number of cells
- \( T \): Time horizon
- \( Q(i,t) \): Successor cells of \( i \) at time \( t \)
- \( P(i,t) \): Predecessor cells of \( i \) at time \( t \)

- **Task Execution Constraints**: Delay in meeting the task deadline

\[
\begin{align*}
t_{\text{depart}}^{\text{loc}(l)} &= t_{\text{start}}^{\text{loc}(l)} + t_{\text{process}}^{\text{loc}(l)}, \forall l, \forall k \in \Psi_{l}^{\text{assign}} & 2(a) \\
t_{\text{start}}^{\text{loc}(l)} &= \max_{k \in \Psi_{l}^{\text{assign}}} t_{\text{arrival}}^{\text{loc}(l)}, \forall l & 2(b) \\
\sum_{j \in P(\text{loc}(l),t)} \sum_{k=1}^{K} x_{j\text{loc}(l)kt} & \leq q_{l}, \forall l, \forall t & 2(c)
\end{align*}
\]

where

- \( t_{\text{depart}}^{\text{loc}(l)} \): Departure time of UAV \( k \)
- \( t_{\text{arrival}}^{\text{loc}(l)} \): Arrival time of UAV \( k \)
- \( q_{l} \): Maximum number of UAVs for task \( l \)
- \( \Psi_{l}^{\text{assign}} \): Set of assigned UAVs for task \( l \)
- \( \text{loc}(l) \): Location of task \( l \)
Multi-Objective MILP Problem Constraints

- **Collision Avoidance Constraints**: Ensures safe path by avoiding collision with obstacles

\[
\begin{align*}
    t_{k'i}^{\text{arrive}} - t_{ki}^{\text{depart}} & \geq \Delta t - M \alpha_{kk'i} \quad \forall i, k, k' \neq k \quad 3(a) \\
    t_{ki}^{\text{arrive}} - t_{k'i}^{\text{depart}} & \geq \Delta t - M (1 - \alpha_{kk'i}) \quad \forall i, k, k' \neq k \quad 3(b) \\
    \alpha_{kk'i} & \in \{0,1\}, \forall i, k, k' \neq k
\end{align*}
\]

where
- \( M \): Large number
- \( \alpha_{kk'i} \): Binary variable indicating when UAV \( k \) arrives after \( k' \)
- \( \Delta t \): Time gap

- **Arrival and Departure Constraints**: Tracks the execution status of tasks

\[
\begin{align*}
    t_{k1}^{\text{arrive}} & = 0, \forall k \quad 4(a) \\
    t_{ki}^{\text{depart}} + t_{k}^{\text{travel}} x_{ijkl} & \leq t_{ki}^{\text{arrive}} + M (1 - x_{ijkl}), \forall k, \forall i, \forall j \neq 1, \forall t \\
    t_{ki}^{\text{depart}} & \geq t_{ki}^{\text{arrive}}, \forall i \notin \{\text{loc}(l)\}, \forall k \\
    t_{ki}^{\text{depart}} & \geq t_{ki}^{\text{arrive}}, \forall i \in \{\text{loc}(l)\}, \forall k \notin \Psi_{l}^{\text{asgn}} \\
    t_{ki}^{\text{arrive}} & = \text{Departure time of UAV } k \text{ from cell } i \\
    t_{ki}^{\text{travel}} & = \text{Travel time of UAV } k \\
    t_{ki}^{\text{arrive}} & = \text{Arrival time of UAV } k \text{ at cell } i
\end{align*}
\]
Multi-Objective UAV Path Planning Results

- **Solution**: Decomposed MILP solution approach:
  - **Phase I**: Minimize the path risk of each UAV given the estimated arrival time at each task location
  - **Phase II**: Minimize the task latency with respect to the arrival time of each UAV at each task location given the path in Phase I

- **Scenario I**: Coordinated path planning in different contexts
  
  a) No manned aircraft
  
  b) One manned aircraft
  
  c) Two manned aircraft
Multi-Objective UAV Path Planning Results

- **Scenario II**: Coordinated path planning around static obstacles

![Scenario II Diagram]

- **Scenario III**: Coordinated path planning around static and dynamic obstacles

![Scenario III Diagram]

- **Scenario I**: An increase in the number of manned aircraft delays the task processing time in order to guarantee safe trajectory planning within a confined mission area

- **Scenario II & III**: Mission tasks are completed on time in a large environment with static and dynamic obstacles
Python Implementation of 3D A* Algorithm

• Given:
  – Mission: Path planning
  – Environment: 3D mission space
  – Asset: UAV
  – Task: Plan path from start point to end point while avoiding static obstacles

• Future Work: 3D path planning for multiple UAVs within a dynamic environment
Python Implementation of 3D A* Algorithm

• Given:
  – **Mission**: Path planning
  – **Environment**: 3D mission space
  – **Asset**: UAV
  – **Task**: Plan path from start point to end point while avoiding static obstacles

• **Future Work**: 3D path planning for multiple UAVs within a dynamic environment
Conclusion

• Summary
  – UAVs are useful for dull, dirty, and dangerous military and civilian operations
  – A multi-objective UAV path planning problem was investigated for coordinated task execution in a dynamic environment including:
    ▪ Mathematical formulation of the path planning problem
    ▪ A two-phase algorithm to solve the resulting MILP problem
  – 3D A* algorithm was implemented in Python

• Future Work
  – Explore approximation techniques, such as ant colony system and genetic algorithms
  – Revise the current planning structure to a distributed setting
  – Explore 3D path planning and address the vertical collision avoidance problem
  – Incorporate pop-up threats and sudden UAV breakdown scenarios
**Future UAV Mission Planning Challenges**

- Provide capabilities more efficiently through *modularity and interoperability*
- Increase in autonomous *multi-platform control*
- More *survivable* with improved and *resilient communications* and security from tampering
- Efficient *manned and unmanned teaming to reduce the number of personnel* required to operate and maintain the systems
- Consider *realistic models* and incorporate/fuse data from different sources

**UAV Mission Planning Objectives**

- *Dynamic coordination* of multiple unmanned vehicles operating on ground, air, and water
- Develop efficient *algorithms to mimic human-like behavior* in unmanned aerial vehicles for proactive decision support
- Data protection and exploitation using *High Performance Computing (HPC)*
- *Reduce operator workload* by improving autonomy using hierarchical mission planning
- Improve *data flow and standard message architectures* for reliable communication

**High Performance Computing Impacts**

- Provides a *consolidated plug-and-play* application architecture
- Improves *scalability and feasibility* for unmanned aerial system vendors
- Improved *battle space awareness* via tasking, collection, processing, exploitation, and dissemination (TCPED) processes, required to translate vast quantities of sensor data into a shared understanding of the environment
- HPC enables *cross domain data sharing* of information and adapts rapidly to changing threats
- HPC addresses the challenges in *cloud computing* and *multilayer security*, communications, open standards, data storage, cost, ease of technology insertion, etc.
References


