Drone mission planning and control

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Drone mission planning and control

- **Audiovisual shooting mission definition.**
- **Multiple drone mission planning.**
- **Multiple drone mission control:**
  - Single drone flight control.
  - Gimbal control.
  - BMMCC control.
  - Multiple drone control architecture.
  - Drone formation control.
- **Collision avoidance.**
Mission Planning Vocabulary

- **MULTIDRONE Shooting Mission**: list of actions.
- Types of actions:
  - **Shooting Actions**: drone + camera
    e.g., Lateral Tracking, Fly-Over, Orbit, …
  - **Navigation Actions**: drone action only, does not involve shooting
    e.g., Take-off, Land, Go-to-waypoint, …
- Shooting Actions are *event-triggered*:
  - A start event is associated to each Shooting Action, which will trigger the action when it occurs.
    E.g., target reaches a milestone, start of race, …
Problem definition

- Given N drones with known positions.
- Given M single-drone tasks with initial position, initial time (event) and time duration.
- Solve a Multi-Robot Task Allocation problem to maximize time that drones are covering shooting tasks.
- Tasks correspond to Director Shooting Actions (SAs). SAs with several drones are split into several single-drone tasks.
Shooting Action Parameters

- **Shot type:**
  - Lateral shot, Orbital shot, etc.

- **Zoom type:**
  - Long shot, Medium shot, Close-up, etc.

- **Start position** for the drone and the camera look-at position.

- **Triggering event.**

- Duration.

- Target ID.
Example mission: Boat race scenario
Example mission: Boat race scenario

From start of race until approaching finish line:
- Drone 1 takes a lateral shot (SA1);
- Drone 2 takes a frontal shot (SA2).

At finish line:
- Drone 1 holds position for photo finish (SA3);
- Drone 2 takes an over-the-shoulder shot (SA4).
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• Multiple drone mission control:
  • Single drone flight control.
  • Gimbal control.
  • BMMCC control.
  • Multiple drone control architecture.
  • Drone formation control.

• Collision avoidance.
Assumptions

• Deterministic model. Target trajectory can be predicted exactly, times for event occurrence too.
• Drones’ positions after executing a task can be predicted.
• In reality there will be uncertainties, include threshold in time event to reach start position before.
• Flying time (battery) bounded. Main objective is not reducing battery consumption but filming as much as possible.
Solution

• Discretize time intervals of each task into subintervals, building a time graph.
• Each graph node encodes position, time and remaining battery.
• Objective: maximize the amount of subintervals that each drone cover (film).
• Modification of Dijkstra’s algorithm solves optimally the time graph for one drone.
• Multi-drone solution computed with greedy strategy: applying the one-drone algorithm iteratively, and removing visited edges in graph.
• In case of several graph solutions covering same number of tasks, choose that with less navigation actions.
High-level pre-production/production mission planning

- **High-level planner** assigns different behaviours/tasks to the multidrone team according to director and environmental requirements.

- The multidrone planner needs to be **scalable** with multiple actors, since on-line re-planning could be needed as events happen or execution is performed.
High-level planner

• Shooting Mission translated to list of Shooting Actions with triggering events.

• Tasks correspond to SAs, multi-drone SAs split into several single-drone tasks.
• Each task has a start location, start time and duration.

• Computes the plan: allocates tasks to drones fulfilling time and precedence constraints (Multi-Robot Task Allocation problem).
• MRTA problem definition:
  • N drones with known positions.
  • M single-drone tasks, each one with its time window.
  • Objective: maximize time where drones are covering (filming) tasks.
Example 1

- This example shows how two drones cover a long task in turns, due to the battery constraint.
Example 2

- 3 drones covering 5 tasks.
- Red and blue drones share one task (red one replaced at time 18 by blue).
- Some tasks could not be filmed entirely.
Path Planner

- This submodule is used by:
  - High-level Planner to estimate drone paths and flying times.
  - Onboard Scheduler to compute a path to a landing position in case of emergency.

- Navigation map implemented as a grid. Obtained from Semantic Map.
  - Semantic annotations are indicated as KML features.
  - Geodesic coordinates translated into Cartesian.
  - No-fly polygons become occupied cells in grid.

Example

- Path from one corner to the other. Buildings labeled as no-fly zones (obstacles represented as red crosses in the grid).
- Solved in 66 ms.
Mission Planning architecture

MULTIDRONE Planning

Dashboard

Director events

Mission Controller

Shooting Mission

Plan

Onboard Scheduler

Drone Actions

Action Executor

Drone Actions

Controllers

Event manager

Events

High-level Planner

Path Planner
Mission Planning/Control
On ground modules

**Mission Controller:**
- Interacts with **High-level Planner** to produce a mission plan.
- Monitors mission execution.
- Asks for replanning if needed.

**Event Manager:**
- Receives, manages and generates events.
- Sends events to drones to start and stop action execution.
### Mission Execution

**On drone modules**

- **Onboard Scheduler:**
  - Receives list of actions.
  - Receives events to trigger action execution.
  - Activates the Action Executer.
  - Sends drone status to ground.

- **Action Executer:**
  - Translates Shooting Actions into desired drone+camera configurations.
  - Interacts with other modules to produce commands for autopilot, camera and gimbal.
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Drone operation/control modes

- **Manual operation:**
  - 1 pilot and 1 cameraman per drone.
  - Scalability and operation cost issues, when multiple drones operate.

- **Automatic operation:**
  - 1 drone or multiple drones.
  - Formation control.
Manual operation/control

- **Manual operation**
  - 1 pilot and 1 cameraman per drone.
  - 2 Radio (TX/RX) links per drone.
- **Pilot radio controls:**
  - On screen telemetry.
  - POV camera.
  - Sticks control drone pitch, roll and yaw.
- **Cameraman radio controls:**
  - Control gimbal and camera parameters.
  - Views AV shooting camera.
- **Scalability concerns.**
Automatic drone operation: Drone as Control System

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Control Objectives – Trajectory Tracking

- Track a trajectory.
- Realistic model.
- Robustness to disturbances.
- Bounded actuation.
- Large basin of attraction.
Drone as Control System

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Rigid-body equations of motion (I)

Reference Frames:

\{I\} Inertial Reference Coordinate System.

\{B\} Body-fixed Reference Coordinate System.

\(p \in \mathbb{R}^3\) – Position of \{B\} relative to \{I\}

\(R \in SO(3)\) – Rotation from \{B\} to \{I\}

\(v \in \mathbb{R}^3\) – Linear velocity of \{B\} relative to \{I\}

\(\omega \in \mathbb{R}^3\) – Angular velocity of \{B\} relative to \{I\}
Rigid-body equations of motion (II)

Kinematics:
\[
\begin{align*}
\dot{p} &= v \\
\dot{R} &= RS(\omega)
\end{align*}
\]

Dynamics:
\[
\begin{align*}
\dot{m} &= f \\
J\dot{\omega} &= -S(\omega)J\omega + n
\end{align*}
\]

\[S(\omega)a = \omega \times a, \text{ for } \omega, a \in \mathbb{R}^3\]

\[m \in \mathbb{R} - \text{ mass}\]

\[J \in \mathbb{R}^{3 \times 3} - \text{ Tensor of inertia expressed in } \{B\}\]

\[f \in \mathbb{R}^3 - \text{ External forces expressed in } \{I\}\]

\[n \in \mathbb{R}^3 - \text{ External moments expressed in } \{B\}\]
Quadrotor dynamic modeling

Two pairs of counter-rotating rotors:

\[
\begin{bmatrix}
T \\
T_x \\
T_y \\
T_z
\end{bmatrix} =
\begin{bmatrix}
1 & 1 & 1 & 1 \\
0 & b & 0 & -b \\
-b & 0 & b & 0 \\
c & -c & c & -c
\end{bmatrix}
\begin{bmatrix}
F_1 \\
F_2 \\
F_3 \\
F_4
\end{bmatrix}
\]

\[
r_3 = Re_3 = R
\begin{bmatrix}
0 \\
0 \\
1
\end{bmatrix}
\]

\[
f_g = mge_3
\]
Quadrotor dynamic modeling

Dynamics:

\[
\begin{align*}
    m \ddot{\mathbf{v}} &= \mathbf{f} \\
    J \ddot{\mathbf{\omega}} &= -S(\mathbf{\omega}) J \mathbf{\omega} + \mathbf{n}
\end{align*}
\]

\[f = -\mathbf{T}_{r3} + \mathbf{f}_{g} + \mathbf{d}\]

\[\mathbf{n} \in \mathbb{R}^3 \quad \text{Torque commands}\]

\[\mathbf{T}_{r3} \in \mathbb{R}^3 \quad \text{Thrust force}\]

\[\mathbf{f}_{g} \in \mathbb{R}^3 \quad \text{Gravitational force}\]

\[\mathbf{d} \in \mathbb{R}^3 \quad \text{Disturbance forces}\]
Quadrotor dynamic modeling

Underactuated system: 12 states, 4 inputs

Flat output \((p, \psi) \in \mathbb{R}^4\)
Drone as Control System

Model Dynamics

Sensors

Controller

Operator

Input

Disturbances

Noise

Output

Noise

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Trajectory Tracking Control

Underactuated system: 12 states, 4 inputs

At rest
\[ T_{r3} = f_g \]
\[ \dot{v} = 0 \]

Accelerating
\[ T_{r3} = f_g - m\dot{v} \]
\[ \dot{v} \neq 0 \]

Control objective:
Steer the position to a desired trajectory
\[ p(t) \rightarrow p_d(t) \]
using \( T_{mn} \) as input.

Can only prescribe 4 states:
e.g. 3D position and rotation about z-axis.
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Trajectory Tracking Control

Simplest Position Controller yields mass-spring-damper system

\[ m \ddot{\tilde{v}} = -k_1 \tilde{p} - k_2 \tilde{v} \]
Hierarchical Control

Explores time-scale separation:

- *Slow* outer-loop dynamics – Position.

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Autopilot – PixHawk 2.1

- Autopilot: Sensors (IMU, GPS, Barometer,…) + Flight Controller.
- Radio Link

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Autopilot – PixHawk 2.1

- **Sensors:**
  For orientation: IMU (accelerometers, gyros, magnetometers).
  For position: GPS, barometer, altimeter, ...

- **Flight Controller:**
  Modes (hierarchical control):
  1. Linear Position control
  2. Linear Velocity control
  3. Angular Position control
  4. Angular Velocity control.

Converted to motor commands
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Gimbal control

- Control objective: Point towards the target.

- Approach: Treat gimbal control independently from drone control.
Gimbal control

- Desired orientation
  \[ \begin{bmatrix} r_1^* \\ r_2^* \\ r_3^* \end{bmatrix} \in \text{SO}(3) \]

Desired optical axis in inertial coordinates
\[ r_3^* = \frac{I_{pT} - I_{pC}}{\| I_{pT} - I_{pC} \|} \]

Camera provides
\[ C \begin{bmatrix} I_{pT} - I_{pC} \\ \| I_{pT} - I_{pC} \| \end{bmatrix} \]
Gimbal control

• Desired orientation

\[
{I}_C R^* = \begin{bmatrix} r_1^* & r_2^* & r_3^* \end{bmatrix} \in SO(3)
\]

Desired optical axis in inertial coordinates

Extra degree of freedom

1st alternative

\[
\begin{align*}
    r_2^* &= \frac{r_3^* \times e_3}{\|r_3^* \times e_3\|} \\
    r_1^* &= r_3^* \times r_2^*
\end{align*}
\]

Keeps camera horizontally aligned

Singularity when pointing exactly downward

\[
    r_3^* = e_3
\]

2nd alternative

Align with target velocity
Gimbal control

- Desired orientation

\[ I_C R^* = \begin{bmatrix} r_1^* & r_2^* & r_3^* \end{bmatrix} \in SO(3) \]

Extra degree of freedom

1st alternative

\[ r_2^* = \frac{r_3^* \times e_3}{||r_3^* \times e_3||} \]
\[ r_1^* = r_3^* \times r_2^* \]
Gimbal control

• Desired orientation

\[ I_C R^* = \begin{bmatrix} r_1^* & r_2^* & r_3^* \end{bmatrix} \in SO(3) \]

Extra degree of freedom
2\textsuperscript{nd} alternative

\[ r_1^* = \Pi r_3^* v_T \]

More suitable for fly-overs
Gimbal control

- Desired orientation: $\frac{I}{C}R^* = [r_1^* \quad r_2^* \quad r_3^*] \in SO(3)$
- Current orientation: $\frac{C}{I}R \in SO(3)$
- Error: $R_{e} = R^T R^*$
- Nonlinear Control law:
  \[ \omega = \omega^* + k S^{-1} (R_e - R_e^T) \]

\[ \omega = \omega^* + k S^{-1} (R_e - R_e^T) \]

\[ \downarrow \]

Feed-forward term: target velocity needed
Gimbal controller – experimental test
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Gimbal controller – experimental tests
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BMMCC Control

• No feedback from the camera

• Two ways of mapping the commands to the controls:

<table>
<thead>
<tr>
<th>Select a particular setting</th>
<th>Increment / decrement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iris</td>
<td>Zoom</td>
</tr>
<tr>
<td>Focus</td>
<td>Start/Stop Recording</td>
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<tr>
<td>Audio</td>
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<td>ISO</td>
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<tr>
<td>Codec</td>
<td>Shutter Angle</td>
</tr>
<tr>
<td></td>
<td>White Balance</td>
</tr>
</tbody>
</table>
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Multidrone Onboard Architecture

Model Dynamics → Autopilot

Autopilot

Sensors (IMU, GPS)

Controller

Output

Onboard CPUs/GPUs

Additional Sensors

Onboard CPUs/GPUs

Perception → Scheduling → Execution

Comms

Gimbal

Navigation Camera

LiDAR

Autopilot

Comms

RTK GPS

LTE / Wifi / RC

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Onboard functional architecture

Onboard CPUs/GPUs

- Perception
- Scheduling
- Execution
- 2D/3D Translator (USEAST)
- Path Planner (USE)
- Visual Shot Analysis (AUTH)
- Onboard Scheduler (USE)
- Action Executor (IST)
- UAL (USE)
- Gimbal Control (IST)
- Camera Control (AUTH)
- Autopilot
- Localization (USE)

MultiDrone

1. Shooting Mission
2. Request plan
3. Request path
4. Computed path
5. Mission plan
6. Safety check
7. Plan status
8. Director events
9. Events
10. Drone actions
11. Drone status
12. Action controllers
13. Control commands
14. Gimbal control
15. Camera control
16. Drone control
17. LIDAR

18. Navigation camera
19. Shooting camera
20. Drone telemetry
21. Geometric map
22. Drone localization
23. Drone position
24. Gimbal status
25. Camera status
26. Target position (2D)
27. 3D Target position (from drone)
28. 3D Target position (from target)
29. 3D Target position
30. Visual information
31. Visual control errors
32. Annotated images
33. Semantic annotations
34. Semantic map

Topics Services
Action Execution

- Onboard Scheduler activates execution of individual drone actions.
  - *Navigation Actions*: Take-off, Land, Go to Waypoint, etc.
  - *Shooting Actions (SA)*: Lateral Tracking, Chase, Still, Orbit, etc.

Shooting actions involve drone control + gimbal control for target tracking.
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Drone Controller

1. Drone Status
2. Target Status
3. Shooting Action parameters
4. Reference
5. Drone Velocity Command

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Leader-following for formation control

- Main idea: Trailer-like behavior for the followers.

In inertial frame:
Translated identical paths

In trailer frame:
Different paths, no superposition
Trailer approach in 2D

F – Follower
T – Target

\[ p_F = p_T - R_z(\chi_F) \begin{bmatrix} d_x \\ d_y \end{bmatrix}^T \]

\[
\begin{bmatrix}
 x_F \\
 y_F
\end{bmatrix}
= \begin{bmatrix}
 x_T \\
 y_T
\end{bmatrix}
- \begin{bmatrix}
 \cos(\chi_F) & -\sin(\chi_F) \\
 \sin(\chi_F) & \cos(\chi_F)
\end{bmatrix}
\begin{bmatrix}
 d_x \\
 d_y
\end{bmatrix}
\]
Trailer approach in 2D

F – Follower
T – Target

\[
p_F = p_T - R_z(\chi_F) \begin{bmatrix} d_x \\ d_y \end{bmatrix}^T
\]

\[
\begin{bmatrix} x_F \\ y_F \end{bmatrix} = \begin{bmatrix} x_T \\ y_T \end{bmatrix} - \begin{bmatrix} \cos(\chi_F) & -\sin(\chi_F) \\ \sin(\chi_F) & \cos(\chi_F) \end{bmatrix} \begin{bmatrix} d_x \\ d_y \end{bmatrix}
\]

\[
(\hat{p}_T, \ddot{p}_T) \xrightarrow{\text{Trajectory generation}} p_F
\]

Target position & velocity  \xrightarrow{\text{Desired Follower Position}}

\[
\chi_F = -\frac{\|\hat{p}_T\|}{d_x} \sin(\chi_F - \chi_T)
\]

\[
p_F = p_T - R_z(\chi_F) \begin{bmatrix} d_x \\ d_y \end{bmatrix}^T
\]

\[
(d_x, d_y) \xrightarrow{\text{Distance parameters}}
\]
Properties

- Trailer-like behaviour
  - Different initial conditions, same asymptotic behavior

- Convergence to a rigid formation
  - Both in 2D and 3D
  - On-the-fly computation

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Trailer approach properties

Without Trailer

With Trailer

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Drone Formation Control

• Shooting Actions (SA) for Target Tracking Trailer approach.

• Examples:
  SA1 – constant relative positions
  SA2 – Orbit trajectory
  SA3 – lateral tracking and top view
Trailer approach properties

Without Trailer

With Trailer

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Trailer approach properties

Without Trailer

With Trailer

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Trailer approach properties

Without Trailer

With Trailer

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Multi-drone Conflict Resolution Problem Definition

• Navigate a team of drones in a shared 3D space without collision.
• Starting configuration to a goal configuration.
• Drones must detect and resolve conflicts in a decentralized manner.
Decentralized 3D collision avoidance

- Collision hull defined as a cylinder (yellow).
- Horizontal conflict when reserved cylinder (green) overlaps with others.
- Vertical conflict when blocking cylinder overlaps with others.
- Cylinders allow drones to brake on time and maneuver to avoid collision.
SITL Simulations

• Simulations with a SITL scheme. Noisy GPS measurements.
• Drones in cube exchanging positions.
• Drones in conflict surround each other creating a virtual roundabout.
• Clearance level: minimum distance of each drone to its nearest neighbor.
SITL Simulations

- Clearance does not decrease with noise. Reserved cylinders overlap but not collision ones.
- Travelled distance and time do not significantly increase with noise.
- Algorithm is robust against noisy position measurements.

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Results

• Preliminary field flights started.
• Drones braking distances quite sensitive to wind.
• Next steps:
  • Integrate sensors for obstacle detection
  • Control drones’ orientation.
Thank you very much for your attention!

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