MULTI AGENT COOPERATIVE PATH PLANNING VIA MODEL PREDICTIVE CONTROL

Christian Kallies, Institut für Flugführung, 23.05.2023

DLR

Goal

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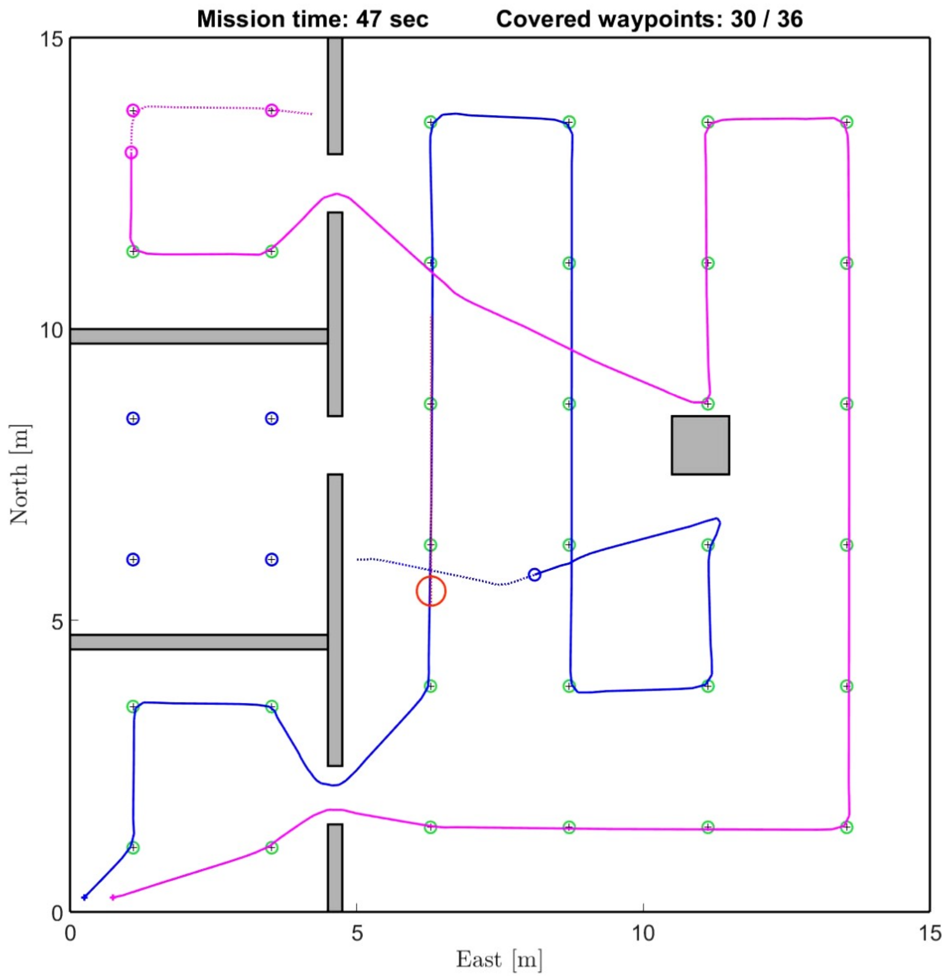
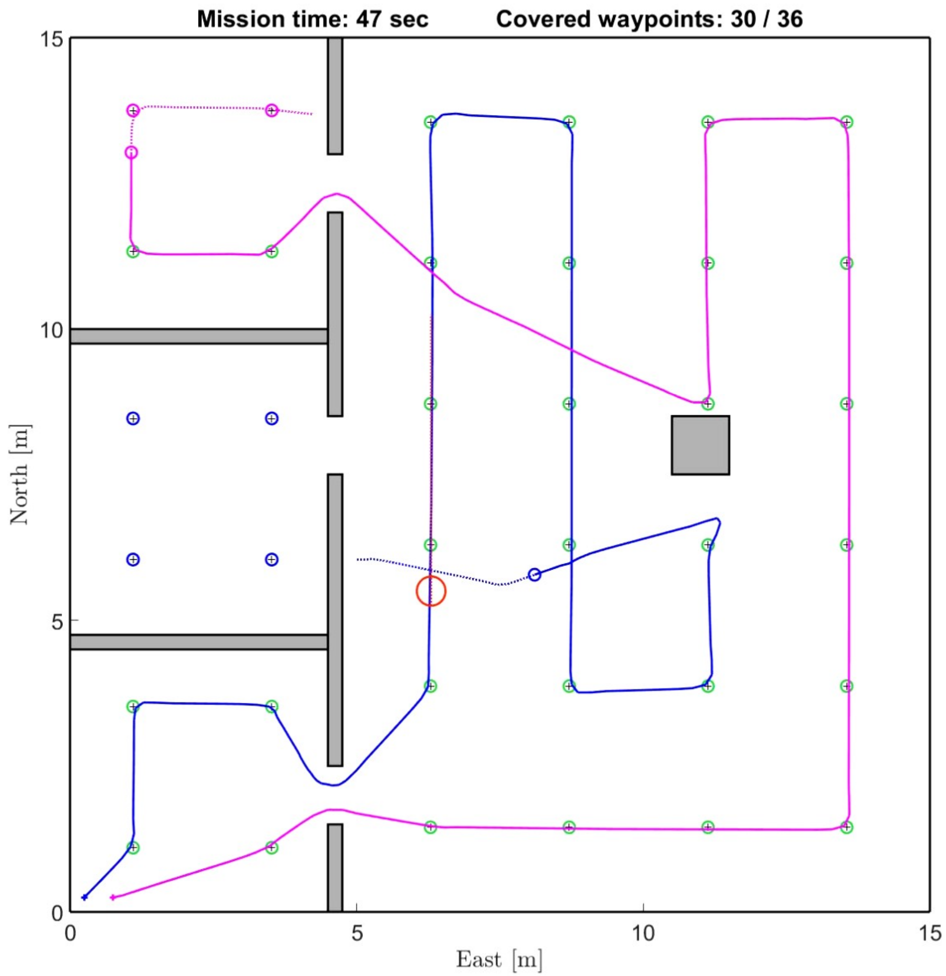
- Cover a specific area using multiple UAS



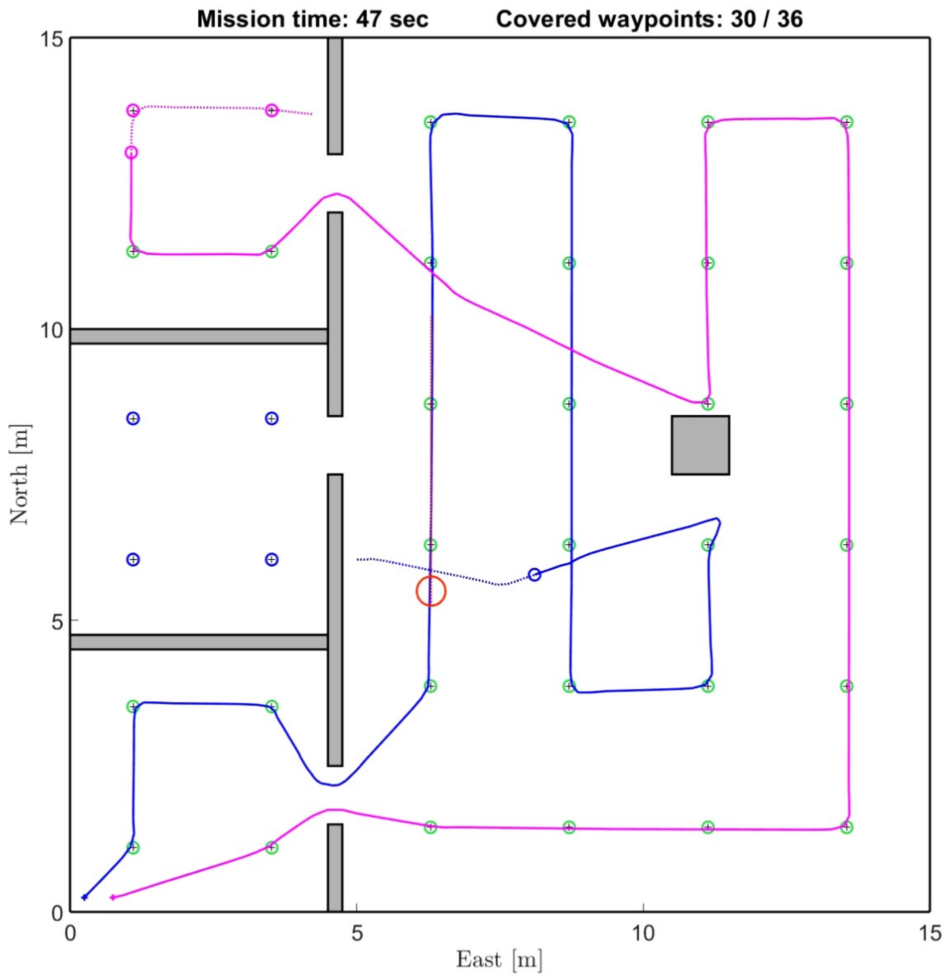
Goal

- Cover a specific area using multiple UAS
- Coverage using waypoints



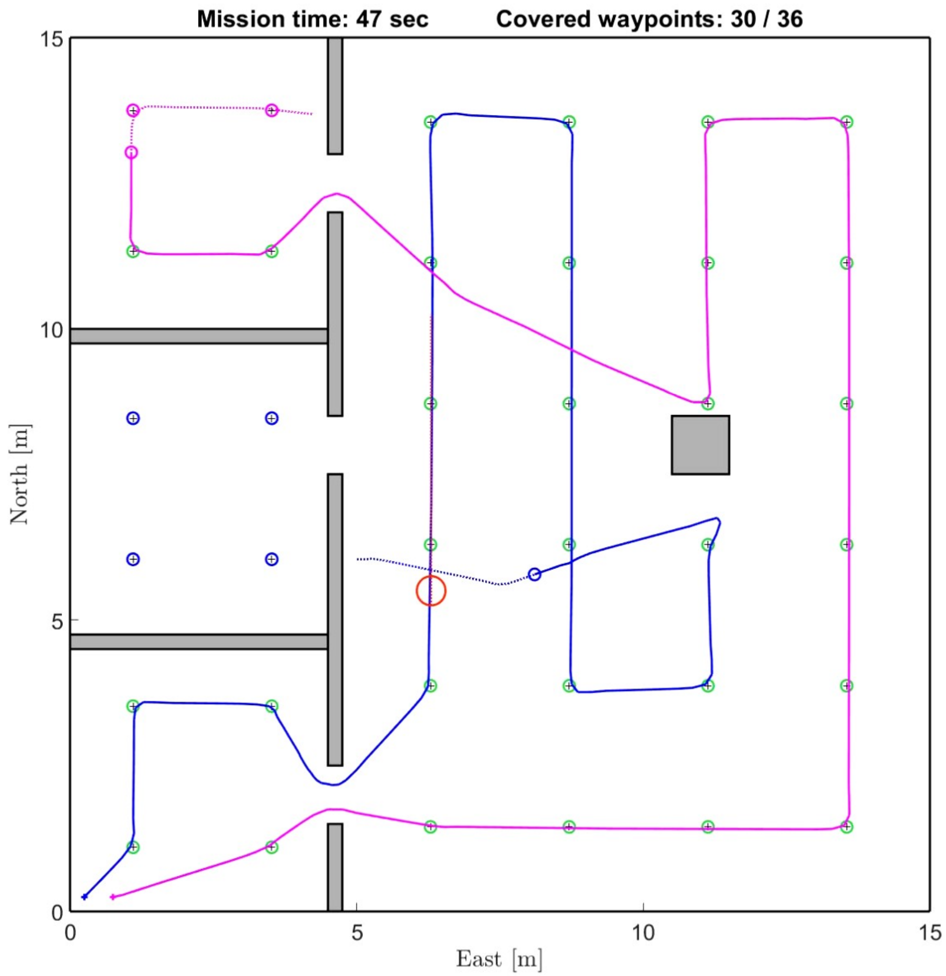
Goal

- Cover a specific area using multiple UAS
- Coverage using waypoints
- Fixed obstacles (geofences, buildings)



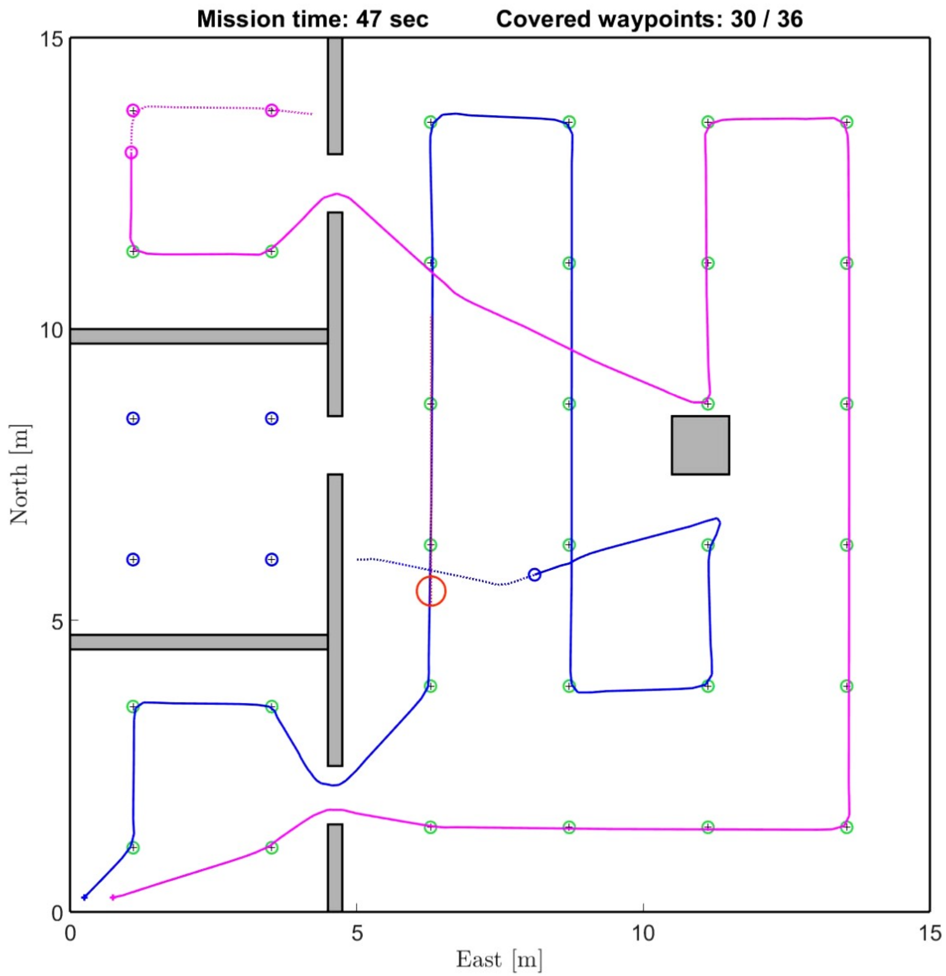
Goal

- Cover a specific area using multiple UAS
- Coverage using waypoints
- Fixed obstacles (geofences, buildings)
- Moving obstacles (uncooperative UAS)



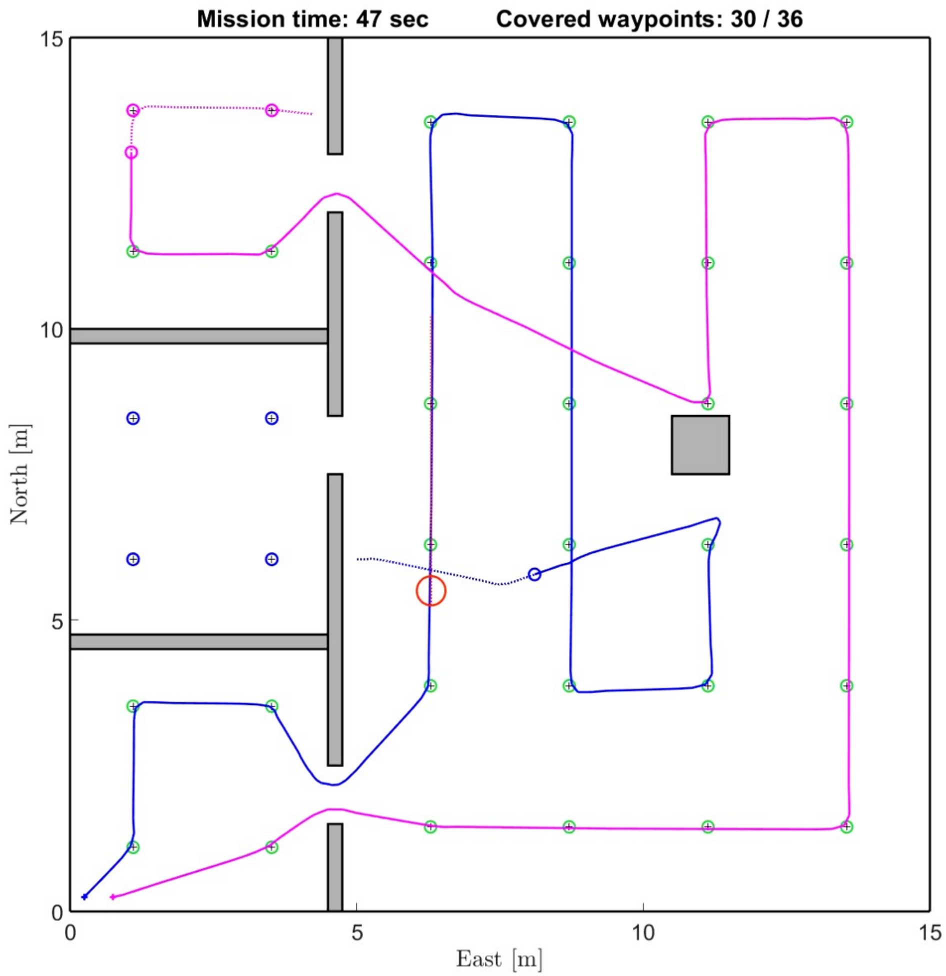
Goal

- Cover a specific area using multiple UAS
- Coverage using waypoints
- Fixed obstacles (geofences, buildings)
- Moving obstacles (uncooperative UAS)
- Cooperative path planning
- Dynamic replanning



Goal

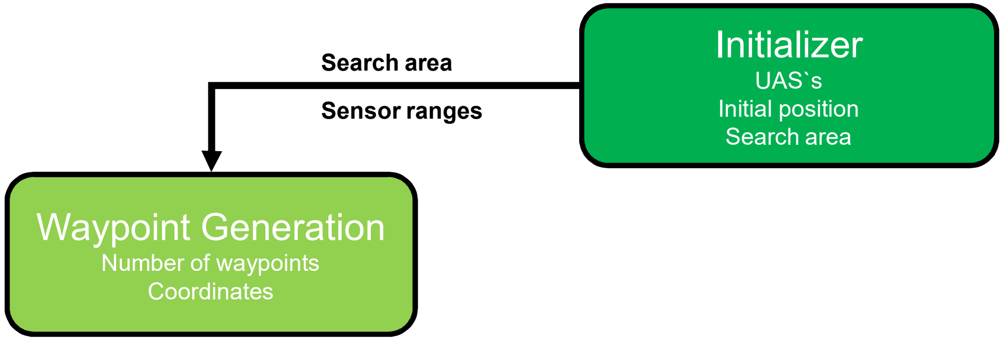
- Cover a specific area using multiple UAS
- Coverage using waypoints
- Fixed obstacles (geofences, buildings)
- Moving obstacles (uncooperative UAS)
- Cooperative path planning
- Dynamic replanning
- Considering vehicle dynamics
  - ➢ ODE`s
  - ➢ Performance model ?



Scheme

Initializer
UAS`s
Initial position
Search area

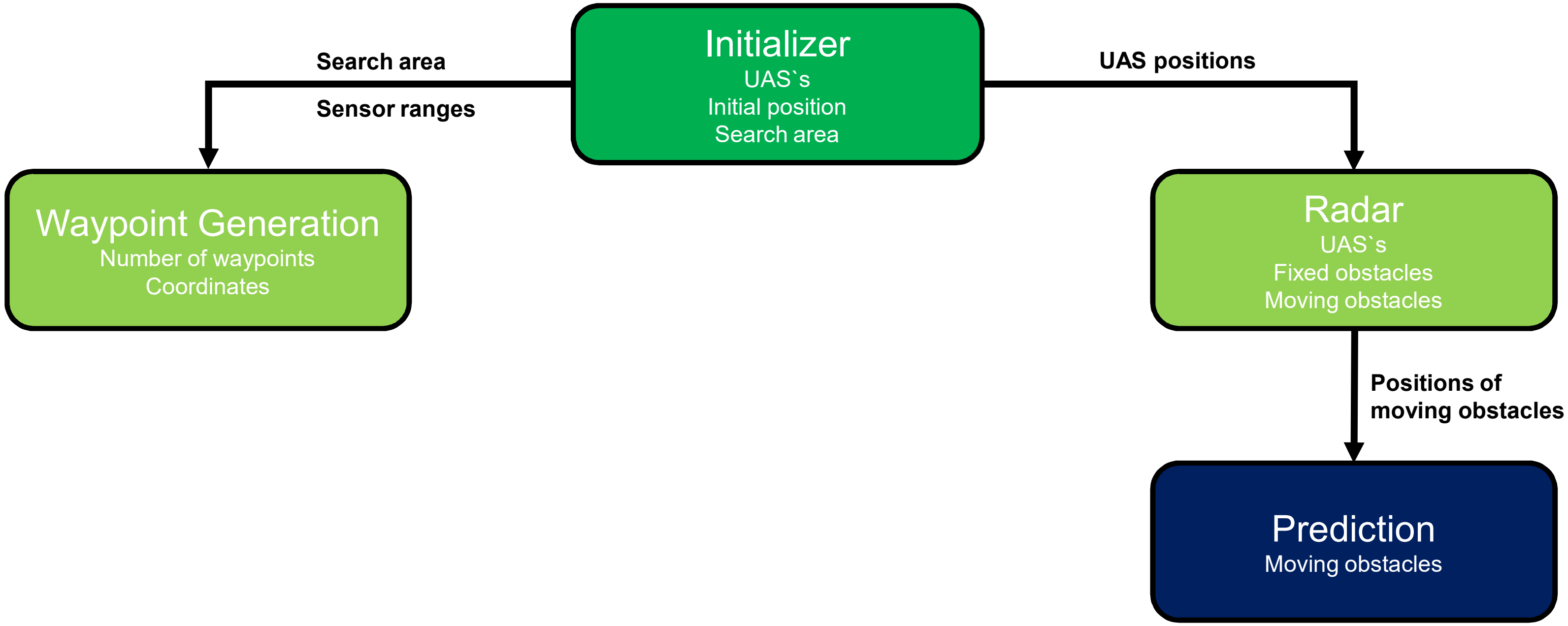
Scheme


Initializer
UAS`s
Initial position
Search area
Search area
Sensor ranges
Waypoint Generation
Number of waypoints
Coordinates

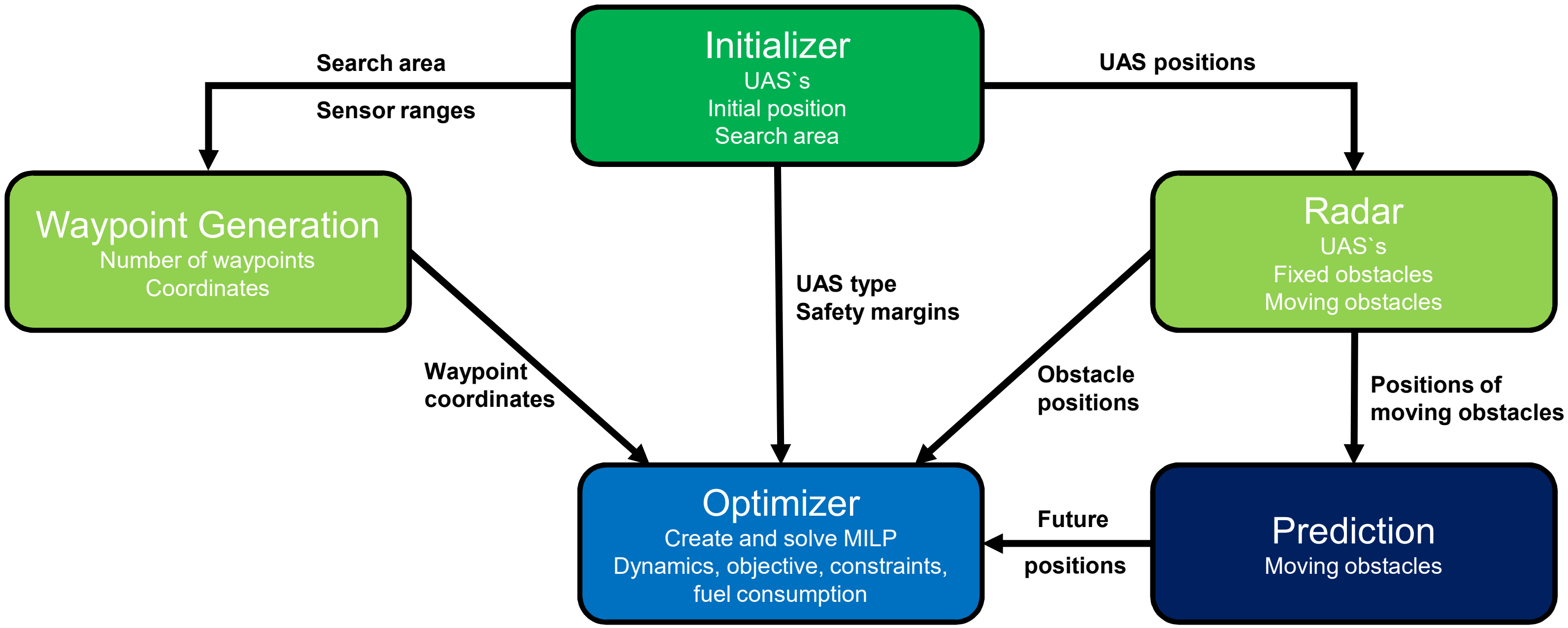
Scheme


Initializer
UAS`s
Initial position
Search area
Search area
Sensor ranges
UAS positions
Waypoint Generation
Number of waypoints
Coordinates
Radar
UAS`s
Fixed obstacles
Moving obstacles

Scheme

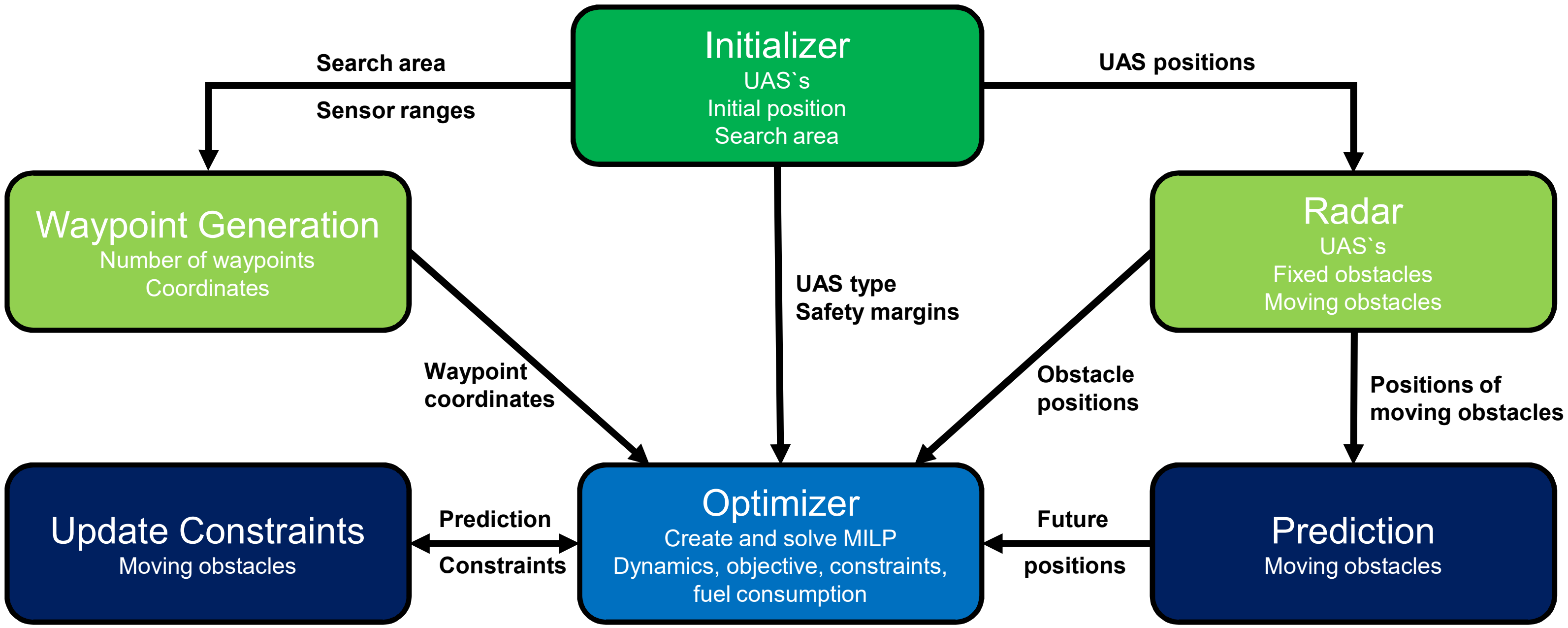

Initializer
UAS`s
Initial position
Search area
Search area
Sensor ranges
UAS positions
Waypoint Generation
Number of waypoints
Coordinates
Radar
UAS`s
Fixed obstacles
Moving obstacles
Positions of
moving obstacles
Prediction
Moving obstacles

Scheme



Initializer
UAS`s
Initial position
Search area
Search area
Sensor ranges
UAS positions
Waypoint Generation
Number of waypoints
Coordinates
Radar
UAS`s
Fixed obstacles
Moving obstacles
UAS type
Safety margins
Waypoint coordinates
Obstacle positions
Positions of moving obstacles
Optimizer
Create and solve MILP
Dynamics, objective, constraints, fuel consumption
Future positions
Prediction
Moving obstacles

Scheme


Initializer
UAS`s
Initial position
Search area
Search area
Sensor ranges
UAS positions
Waypoint Generation
Number of waypoints
Coordinates
Radar
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Fixed obstacles
Moving obstacles
UAS type
Safety margins
Waypoint
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Obstacle
positions
Positions of
moving obstacles
Update Constraints
Moving obstacles
Prediction
Constraints
Optimizer
Create and solve MILP
Dynamics, objective, constraints,
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Future
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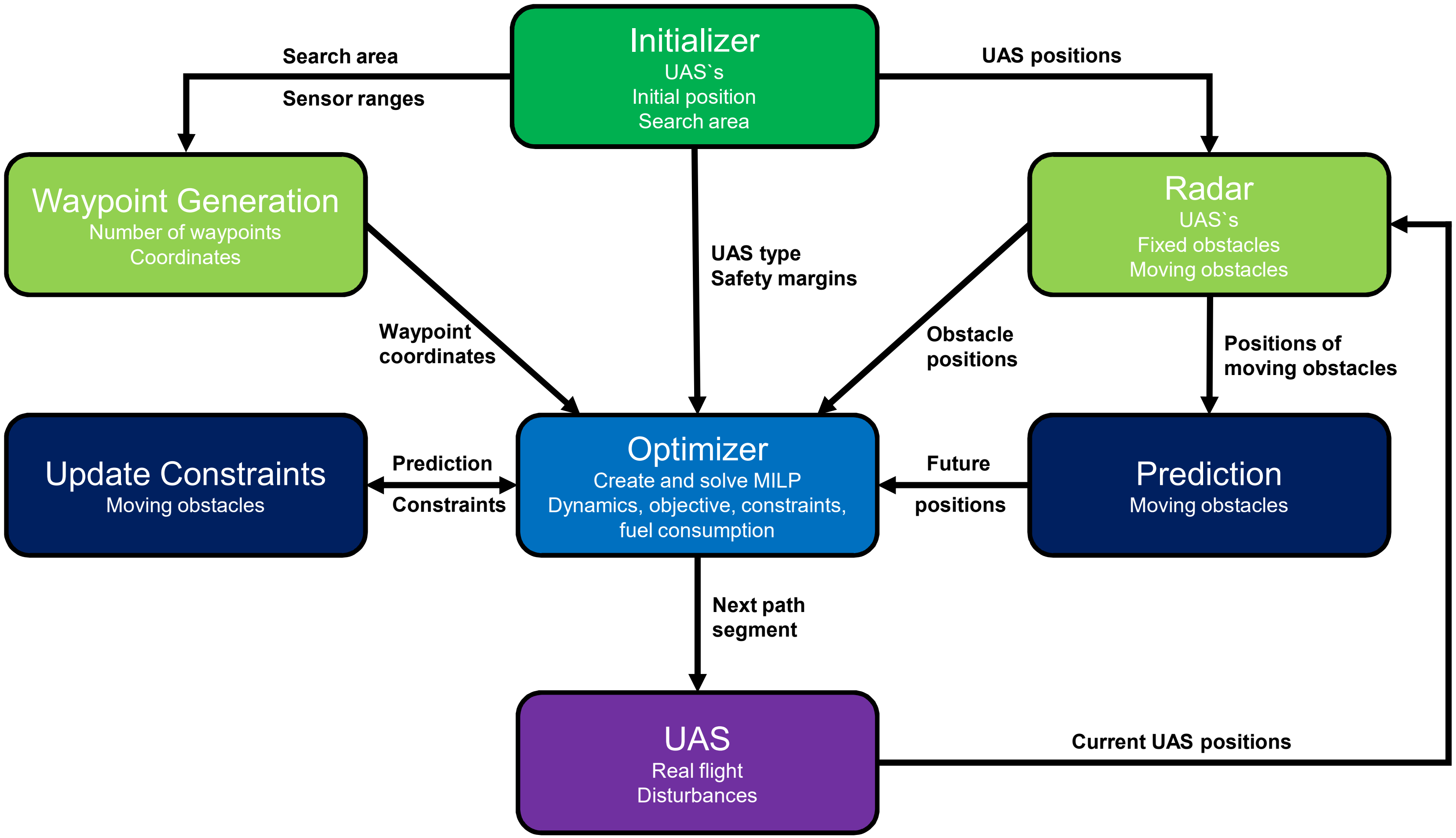
Scheme



Initializer
UAS`s
Initial position
Search area
Search area
Sensor ranges
UAS positions
Waypoint Generation
Number of waypoints
Coordinates
Radar
UAS`s
Fixed obstacles
Moving obstacles
UAS type
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Waypoint
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Positions of
moving obstacles
Update Constraints
Moving obstacles
Prediction
Constraints
Optimizer
Create and solve MILP
Dynamics, objective, constraints,
fuel consumption
Future
positions
Prediction
Moving obstacles
Next path
segment
UAS
Real flight
Disturbances
Current UAS positions

Mathematical Setup

Mathematical Setup

$$\min_{u_i(.),v_j(.)} \sum_{k=0}^{N-1} \left(\sum_{i=1}^{n_{\mathrm{UAV}}} W_{u,i} \cdot |u_i(k)| + \sum_{j=1}^{n_{\mathrm{WP}}} W_{z,j} \cdot z_j(k) \right)$$

$$\begin{aligned}
\text{s.t. } \forall k \in \{0,\ldots,N-1\},\ i \in \{1,\ldots,n_{\mathrm{UAV}}\},& \\
j \in \{1,\ldots,n_{\mathrm{WP}}\}& \\
x_i(k+1) &= A_i x_i(k) + B_i u_i(k) \\
x_i(k) &\in \mathbb{X}_i(k),\ u_i(k) \in \mathbb{U}_i(k) \\
z_j(k+1) &= z_j(k) - v_j(k) \\
v_j(k) &\leq d_j(k) \\
z_j(k) &\in [0,1],\ v_j(k) \in [0,1] \\
d_j(k) &= 1 \Rightarrow \exists\, \hat{i} \in \{1,\ldots,n_{\mathrm{UAV}}\} : \\
&\qquad \mathrm{dist}(\mathrm{UAV}_{\hat{i}}, \mathrm{WP}_j) \leq D
\end{aligned}$$

Mathematical Setup

$$\min_{u_i(.),v_j(.)} \sum_{k=0}^{N-1} \left(\sum_{i=1}^{n_{\mathrm{UAV}}} W_{u,i} \cdot |u_i(k)| + \sum_{j=1}^{n_{\mathrm{WP}}} W_{z,j} \cdot z_j(k) \right)$$

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- Minimize the cost of energy consumption and penalty terms from uncovered waypoints

Mathematical Setup

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- Minimize the cost of energy consumption and penalty terms from uncovered waypoints
- Prediction horizon N, number of waypoints n_{WP}, number of UAS n_{UAS}

Mathematical Setup

$$\min_{u_i(.),v_j(.)} \sum_{k=0}^{N-1} \left(\sum_{i=1}^{n_{\mathrm{UAV}}} W_{u,i} \cdot |u_i(k)| + \sum_{j=1}^{n_{\mathrm{WP}}} W_{z,j} \cdot z_j(k) \right)$$

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- Minimize the cost of energy consumption and penalty terms from uncovered waypoints
- Prediction horizon N, number of waypoints n_{WP}, number of UAS n_{UAS}
- Linearized system dynamics

Mathematical Setup

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- Minimize the cost of energy consumption and penalty terms from uncovered waypoints
- Prediction horizon N, number of waypoints n_{WP}, number of UAS n_{UAS}
- Linearized system dynamics
- Linear constraints for the state and input variables

Mathematical Setup

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- Waypoint dynamics (0 ~ covered, 1 ~ uncovered)

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- Minimize the cost of energy consumption and penalty terms from uncovered waypoints
- Prediction horizon N, number of waypoints n_{WP}, number of UAS n_{UAS}
- Linearized system dynamics
- Linear constraints for the state and input variables
- Waypoint dynamics (0 ~ covered, 1 ~ uncovered)
- Artificial input and constraints

Mathematical Setup

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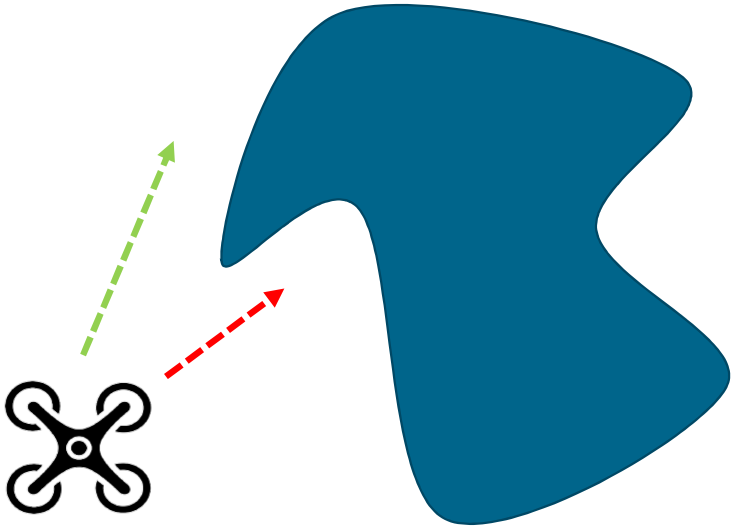
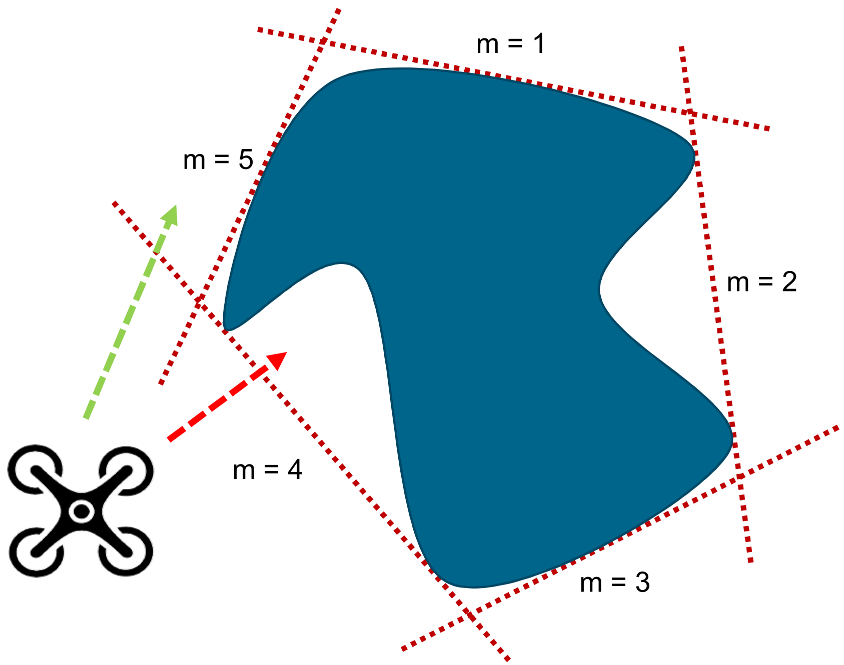
- Minimize the cost of energy consumption and penalty terms from uncovered waypoints
- Prediction horizon N, number of waypoints n_{WP}, number of UAS n_{UAS}
- Linearized system dynamics
- Linear constraints for the state and input variables
- Waypoint dynamics (0 ~ covered, 1 ~ uncovered)
- Artificial input and constraints
- Distance condition for the waypoints

Constraints



Constraints

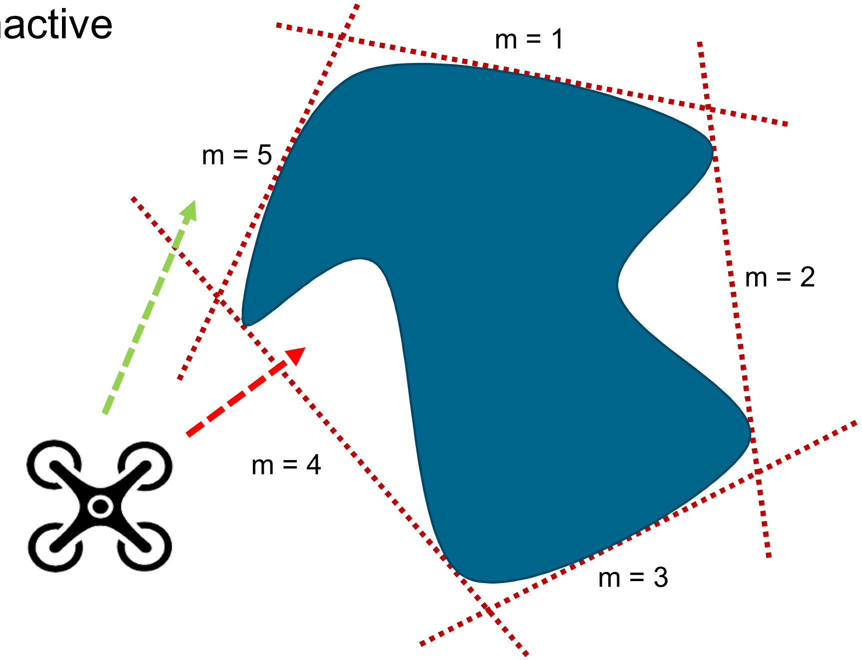
- Nonlinear constraints are approximated via affine functions



Constraints

- Nonlinear constraints are approximated via affine functions
- Binary decision variables are used to set constraints active/inactive

$$\left(x_{\mathrm{UAS},i}(k) - x_{\mathrm{obs,j}}(k)\right) \cdot \cos\left(\frac{2\pi m}{M}\right) + \left(y_{\mathrm{UAS},i}(k) - y_{\mathrm{obs},j}(k)\right) \cdot \sin\left(\frac{2\pi m}{M}\right) \geq \delta_{\mathrm{UAS,obs}} - M_{\mathrm{big}} \cdot \beta_{i,j,m}(k)$$



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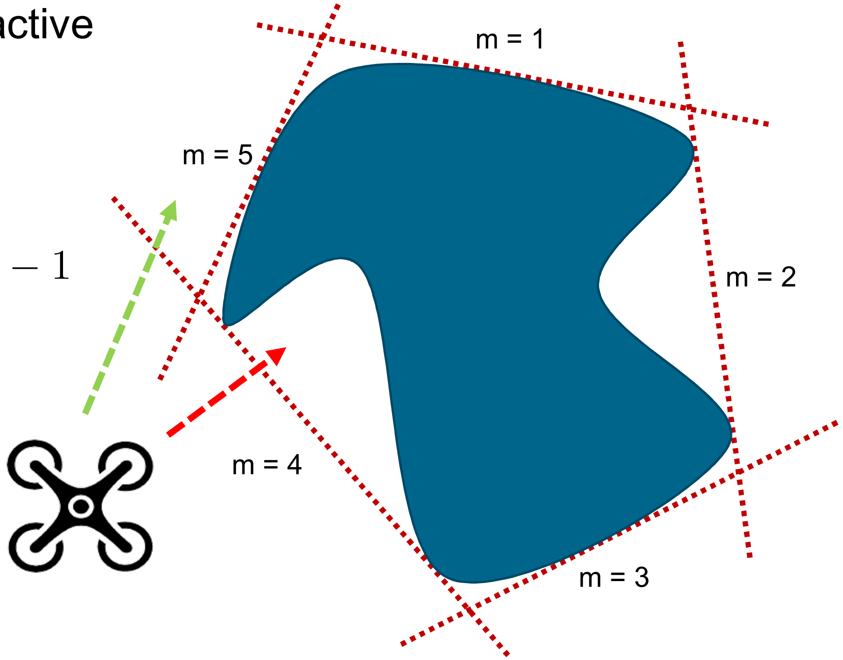
$$\sum_{m=1}^{M} \beta_{i,j,m}(k) \leq M - 1$$



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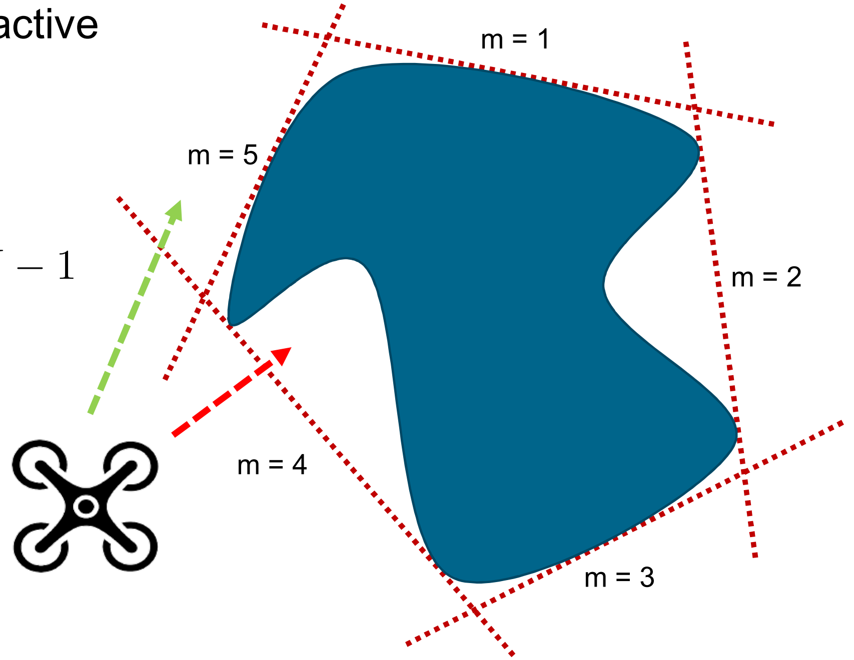

- Waypoint coverage constraints are handled similarly

Constraints

- Nonlinear constraints are approximated via affine functions
- Binary decision variables are used to set constraints active/inactive

$$\left(x_{\mathrm{UAS},i}(k) - x_{\mathrm{obs,j}}(k)\right) \cdot \cos\left(\frac{2\pi m}{M}\right) + \left(y_{\mathrm{UAS},i}(k) - y_{\mathrm{obs},j}(k)\right) \cdot \sin\left(\frac{2\pi m}{M}\right) \geq \delta_{\mathrm{UAS,obs}} - M_{\mathrm{big}} \cdot \beta_{i,j,m}(k)$$

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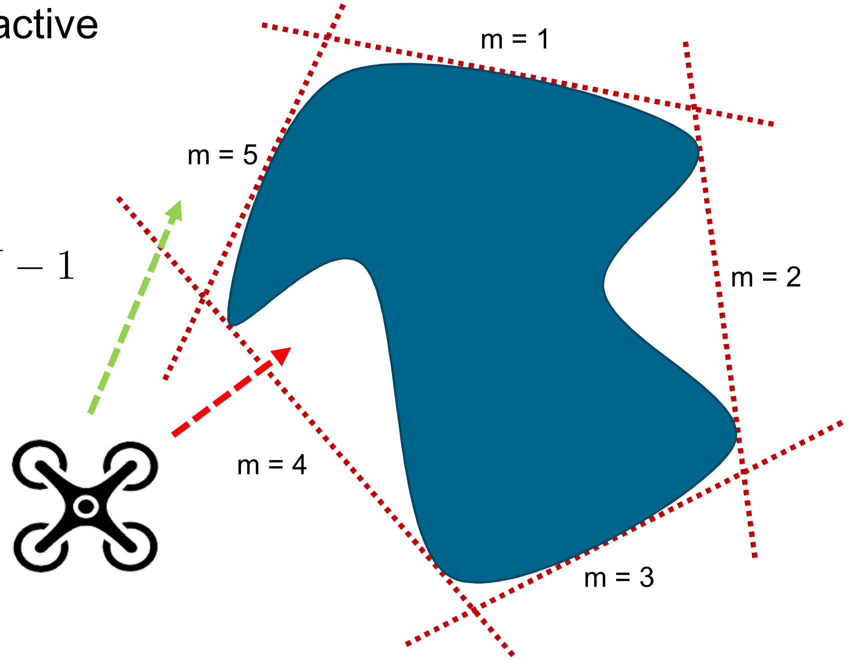
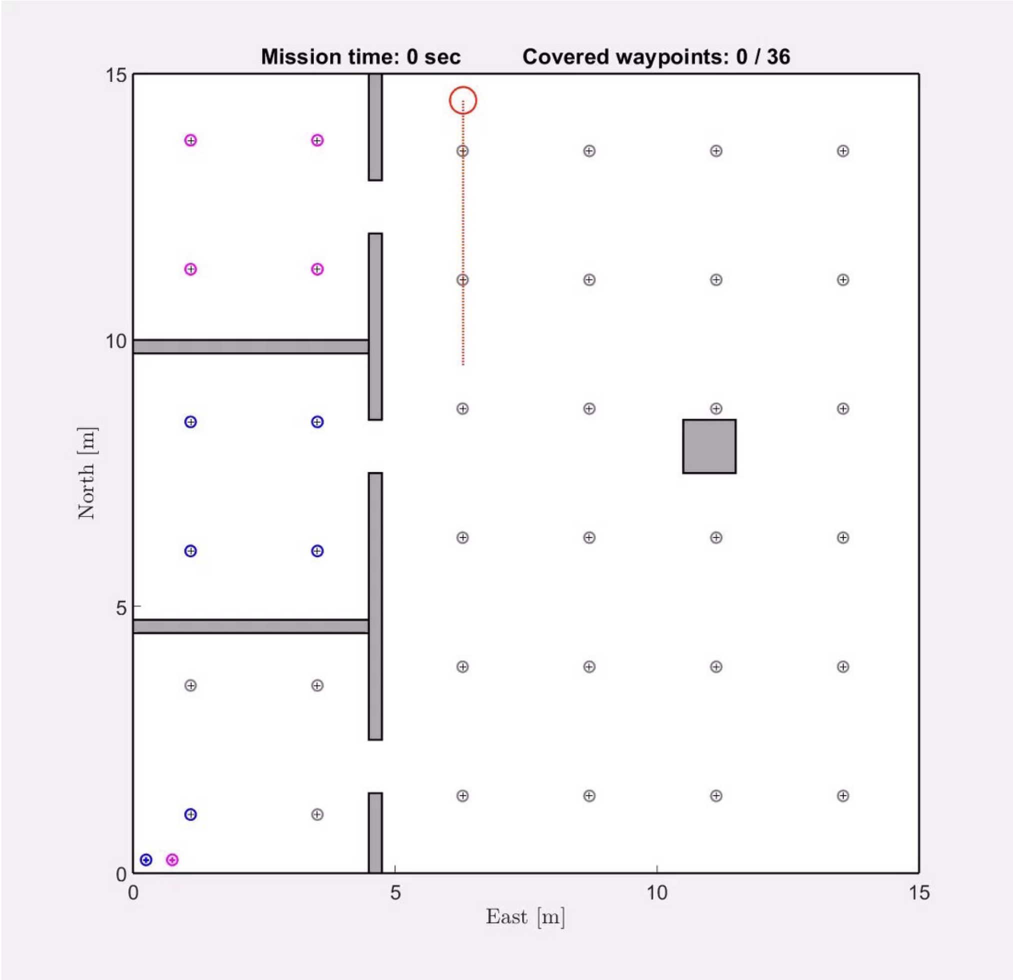


- Waypoint coverage constraints are handled similarly
- The number of binary variables can be decreased

Simulation Results

- Area ~ 15 m x 15 m
- Prediction horizon ~ 5 s, 20 evaluation points

- 2 searching quadcopter (blue and magenta), 11 states, 4 input variables
- 1 moving obstacle (red)
- Predictions (dotted)
- 7 fixed obstacles (grey)
- 36 equidistant waypoints
  - Uncovered (grey)
  - Covered (green)
  - Only one drone can cover (blue, magenta)



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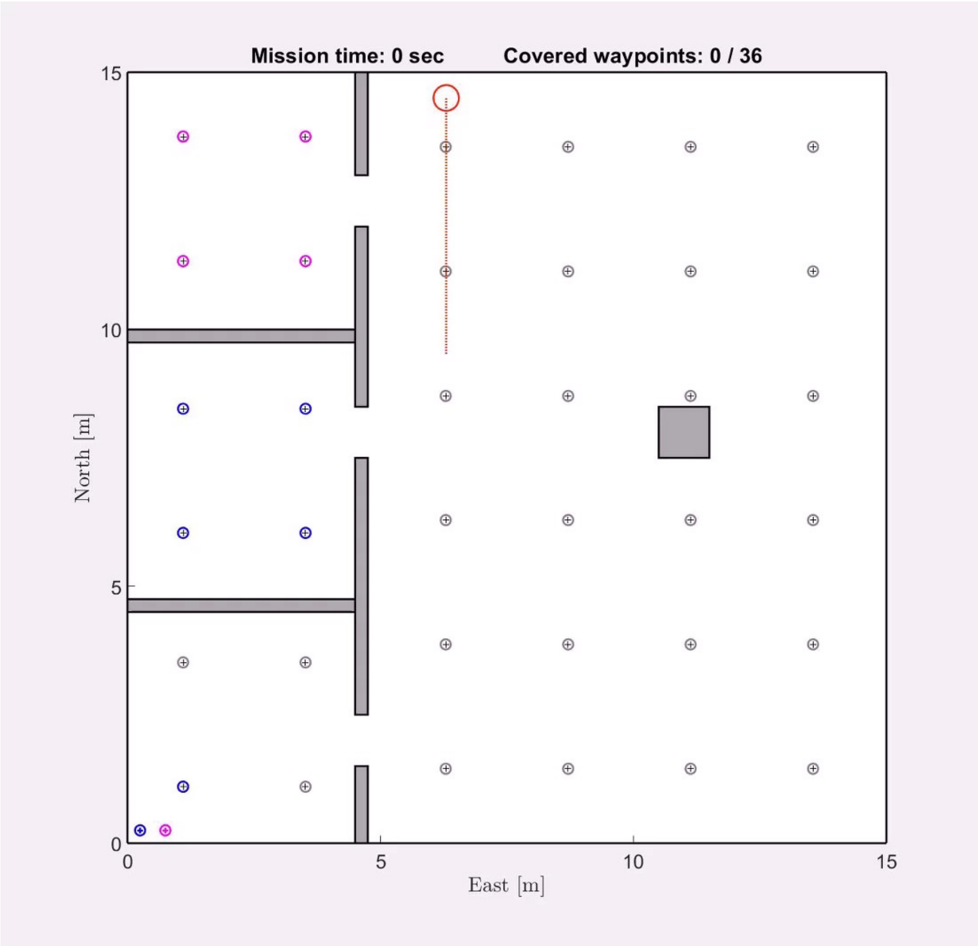

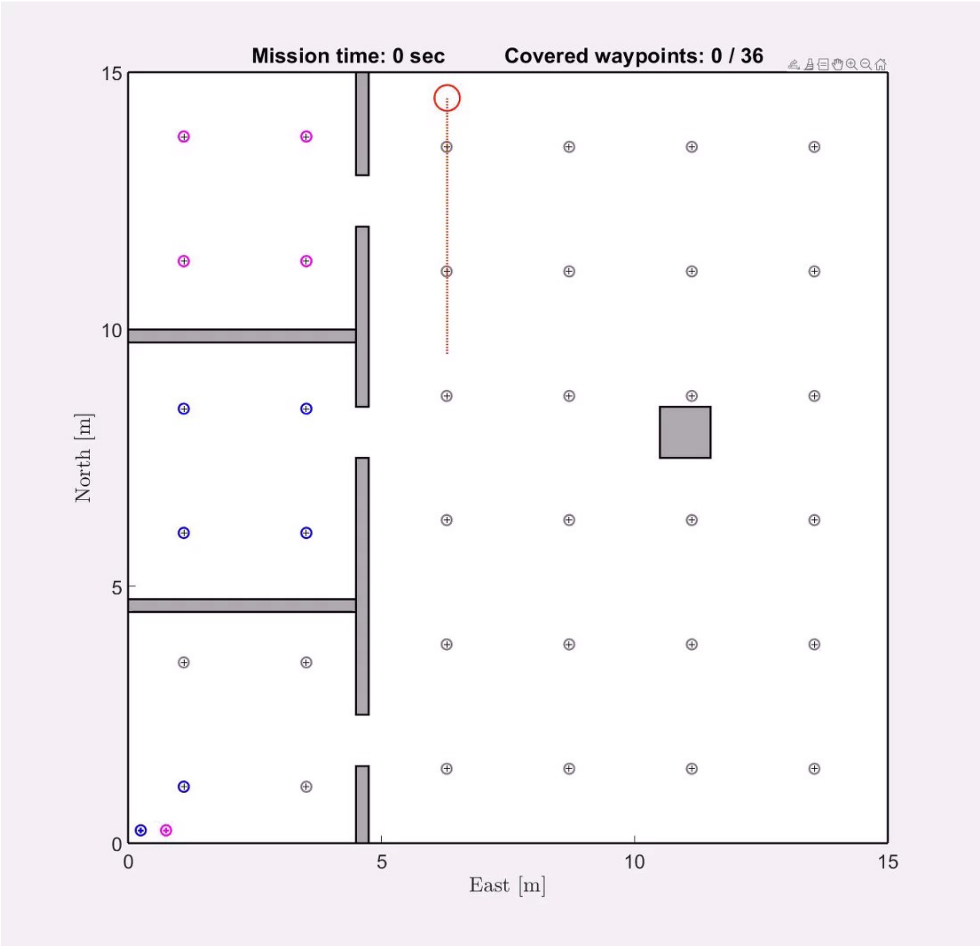

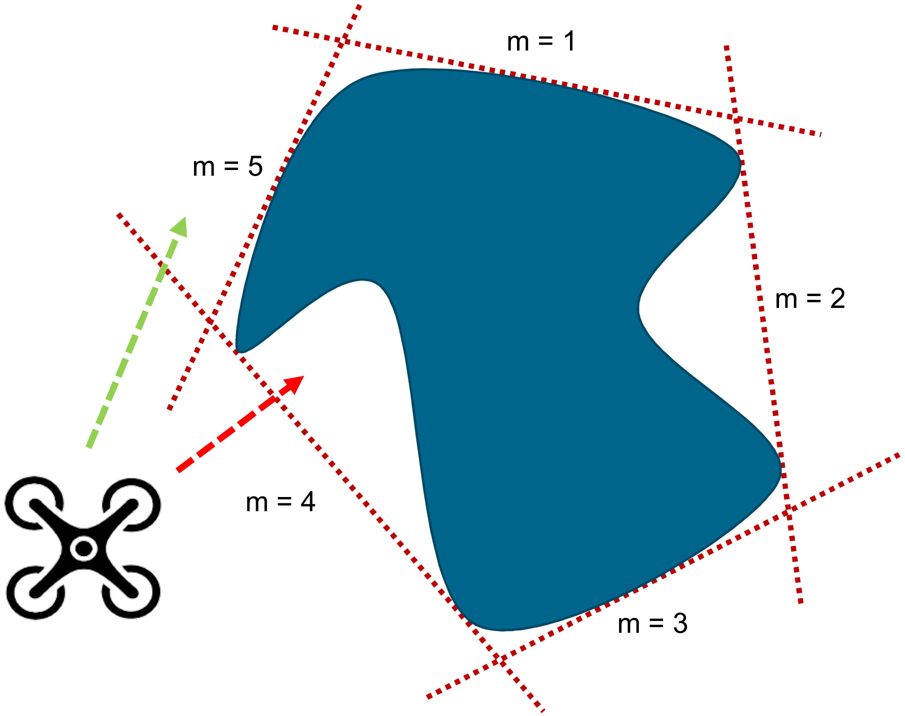
m = 1
m = 5
m = 2
m = 4
m = 3