Model-based Programming for Cooperating Vehicles

16.412 Group Project

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Model-based Embedded & Robotic Systems

CSAIL

Cooperative Model-based Program Architecture

Control Program
- Team mission objectives & coordination constraints
- Team strategies & tactics
- Options & contingencies

System Model
- Terrain map
- Threats and assets
- Vehicle commands and resource models.

Control Sequencer

Selects Feasible Mission Plan from Options

Mission State (Current & Predicted)

Desired Sequence of Mission States (Mission Plan)

Model-based Executive

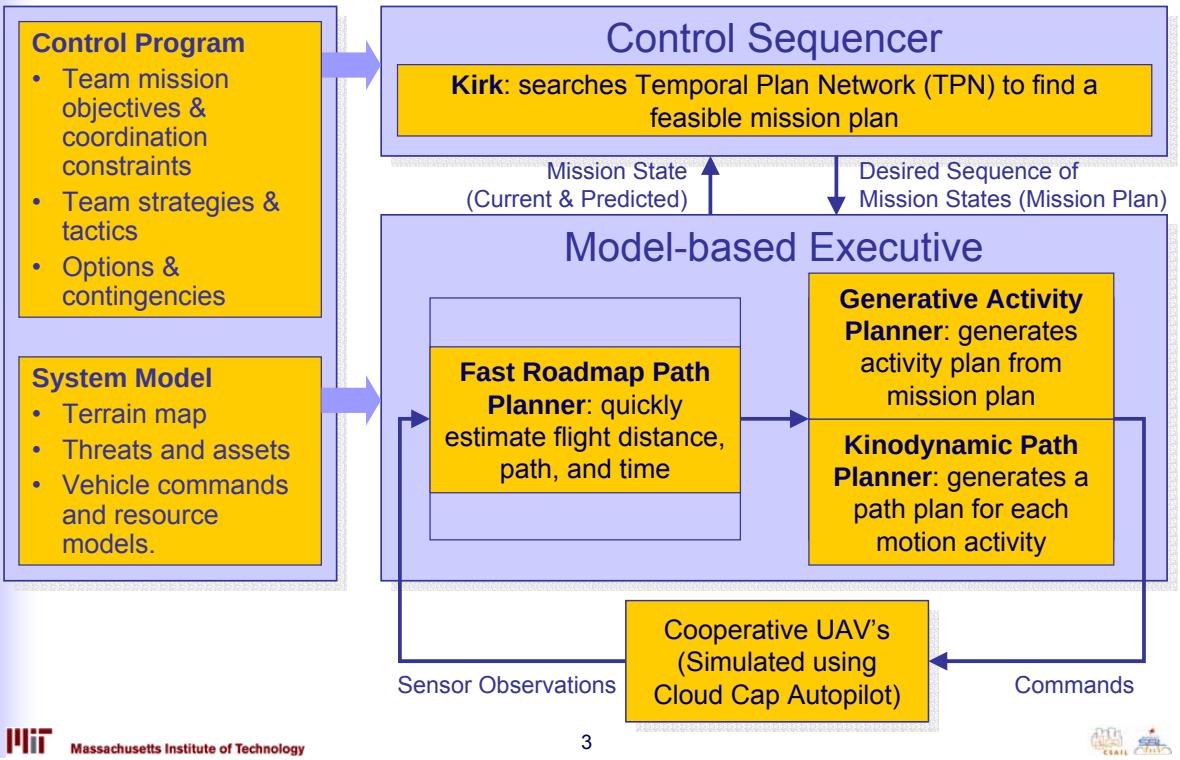
Estimation and Prediction

Activity and Path Planning

Sensor Observations

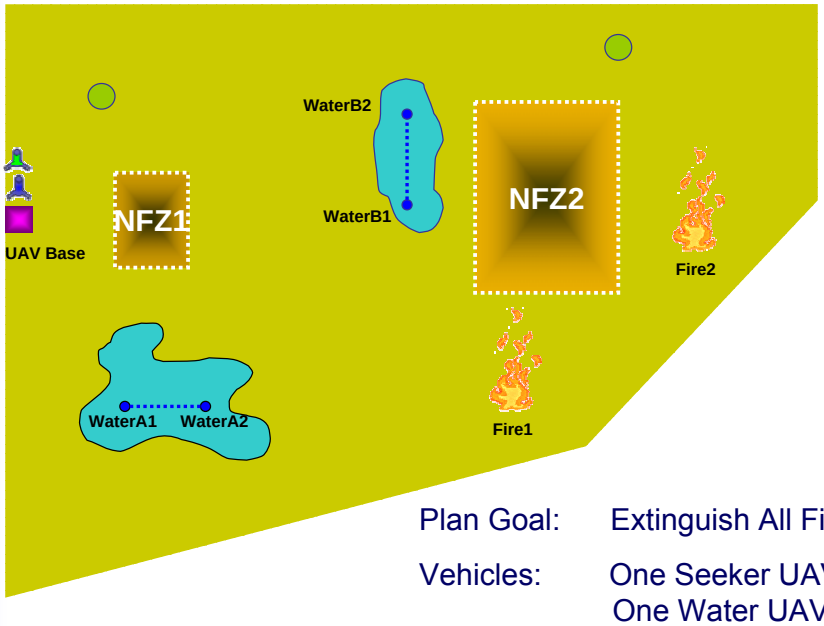
Commands

Cooperative Model-based Program Architecture



Forest Firefighting with Cooperative UAV's

Cooperative Forest Fire Fighting Scenario



Legend:

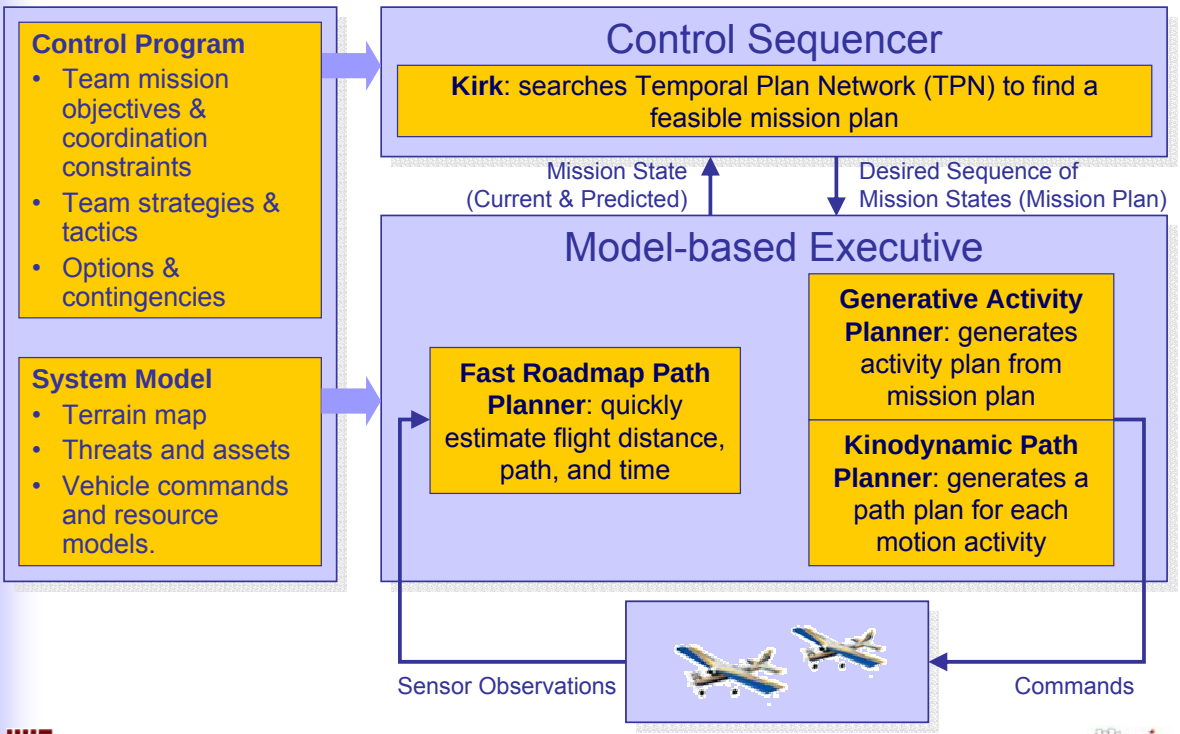
- Seeker UAV
- Water UAV
- No-Fly Zone
- Fire
- Water
- UAV Base
- Refueling Station

Plan Goal: Extinguish All Fires

Vehicles: One Seeker UAV (to image the fires)
One Water UAV (to extinguish fires)

Resources: Fuel & Water

Cooperative Model-based Program Architecture



Robert Effinger's Contributions

1. Created Interface between the high-level planner (Kirk) and the Path Planner (dStarLite)
   (*jointly with Dan Lovell)
2. Created framework in Kirk to solve TPN as a dynamic CSP
3. Implemented Dynamic Backtracking within Kirk

Interface Between Kirk and dStarLite

```
(overall fire-fighting strategy ()
  (sequence
    (choose
      (sequence
        (seeker-uav0.take-image(fire1) [5,10])
        (seeker-uav0.take-image(fire2) [4,10]))
      (sequence
        (seeker-uav0.take-image(fire2) [2,10])
        (seeker-uav0.take-image(fire1) [3,10]))) [0,6]
    (choose
      (sequence
        (water-uav().drop-water(fire1)|20, inf ])
        (water-uav().drop-water(fire2)|15, inf ]))
      (sequence
        (water-uav().drop-water(fire2)|30, inf ])
        (water-uav().drop-water(fire1)|20, inf ]))) [0,45]
    (parallel
      (seeker-uav().return-to-base(base10[ 0 , inf ])
      (water-uav().return-to-base(base0180 , inf ])))
                                                  [0,20]
;; Macro to ask path-planner to update lower bound
;; (water-uav().dStarLite(10 15 20 30 40 50) [0,inf])
```

Operator inputs detailed mission scenario:

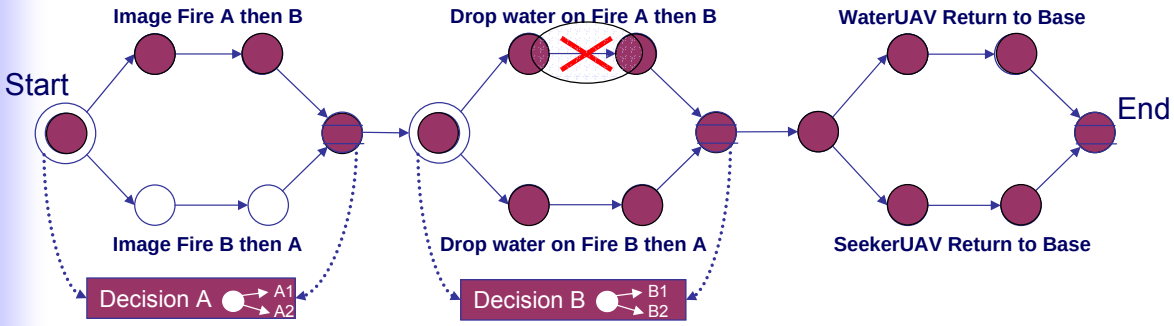
1. Choose which order to image Fire 1 and Fire2
2. Choose which order to drop water on Fire 1 and Fire2
3. UAVs Return to Base together
4. Update lower timebound using path-planner

Solving a TPN as a Dynamic CSP

- Choice Node

- Choice End Node

- Partial Solution is purple

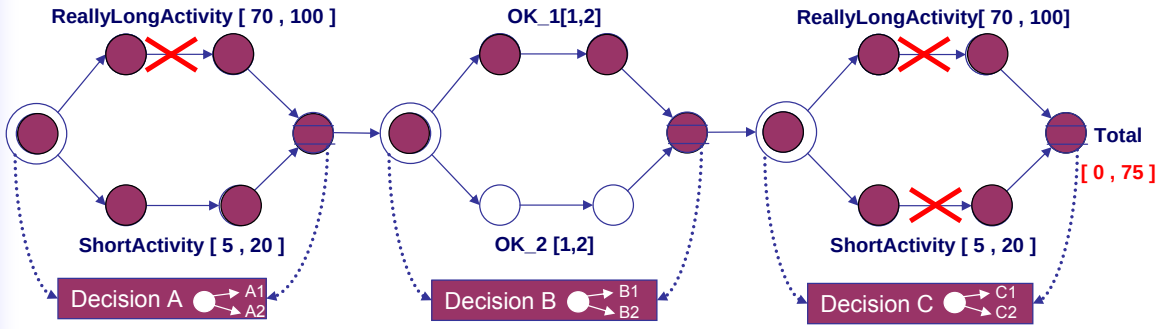


2 Main Functions:

1.) getNextDecisionStartNodes()

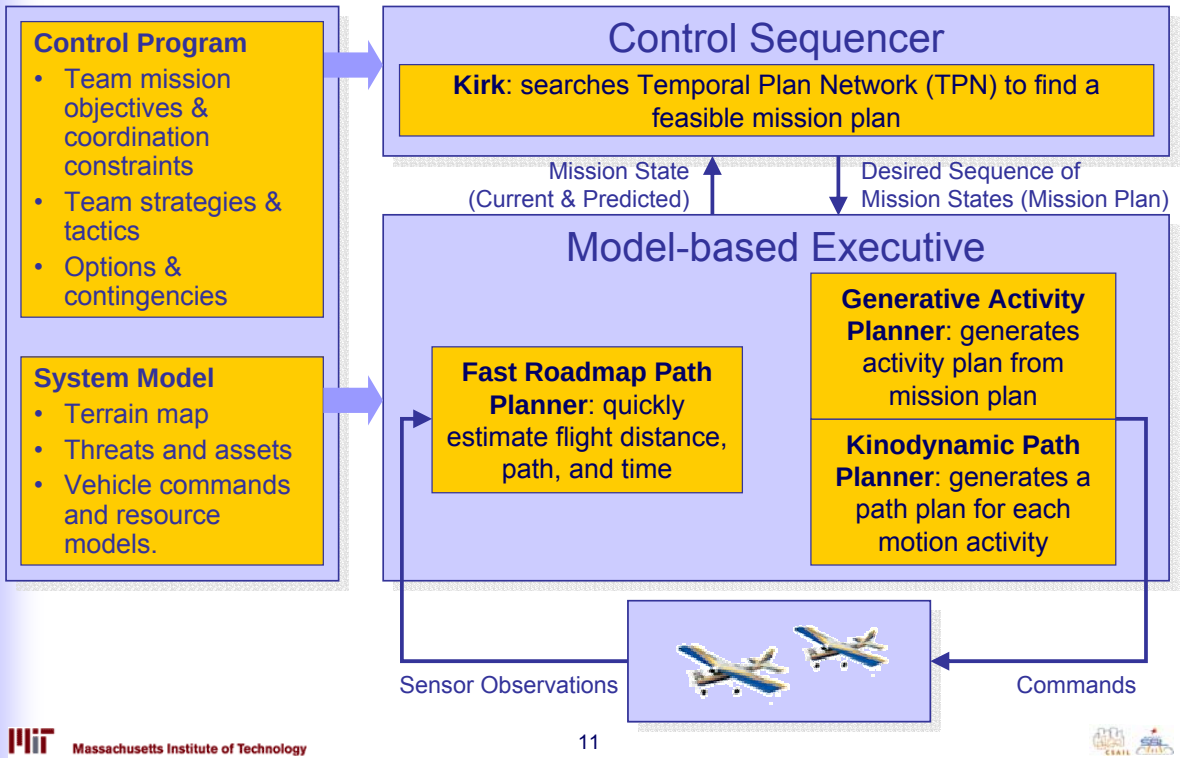
2.) deactivateNestedDecisionNodes()

Dynamic Backtracking Implementation

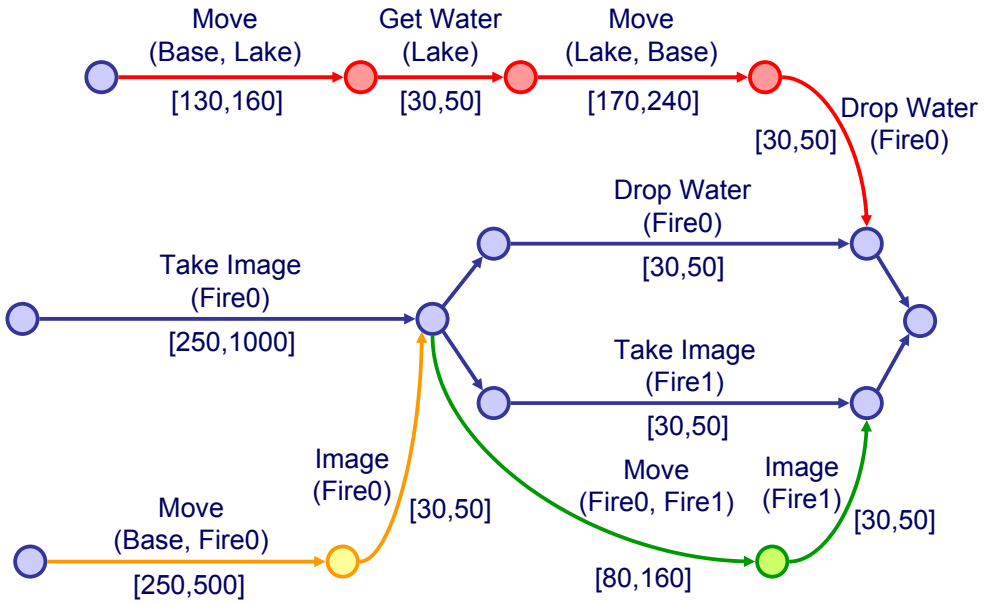


- Backtracks to the source of the problem
- Keeps variable assignments that aren't part of the problem.

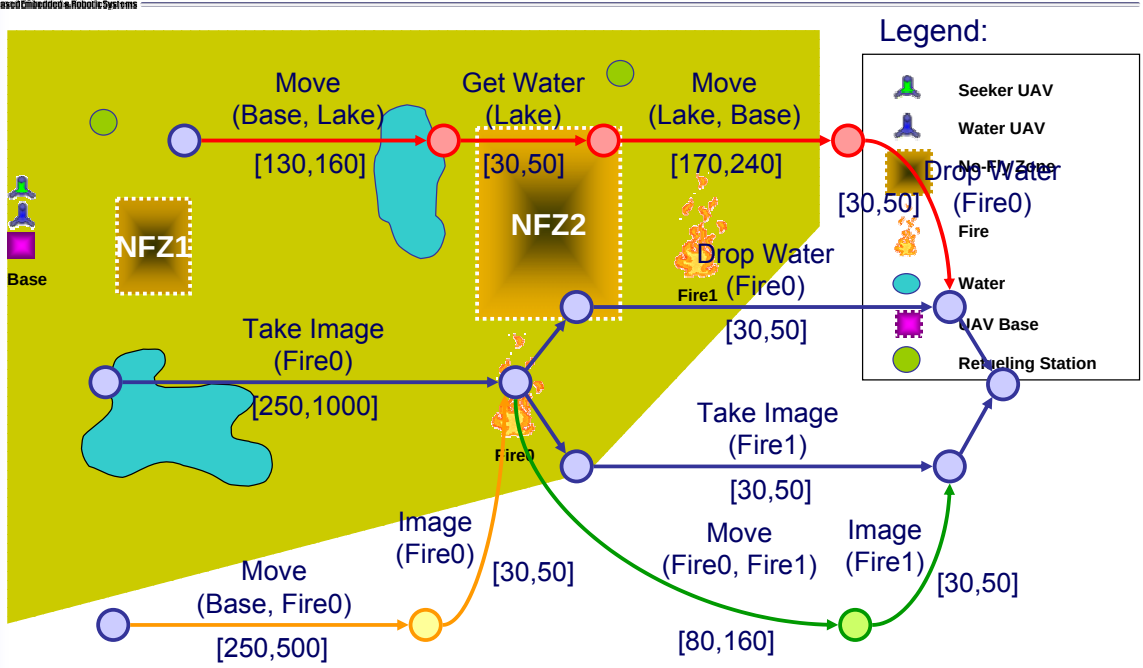
Cooperative Model-based Program Architecture



Mission Plan to Activity Plan



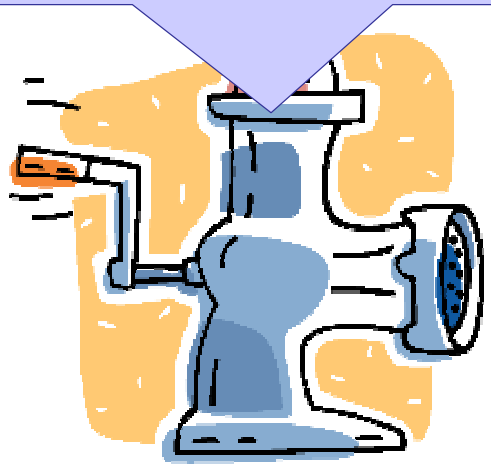
Mission Plan to Activity Plan



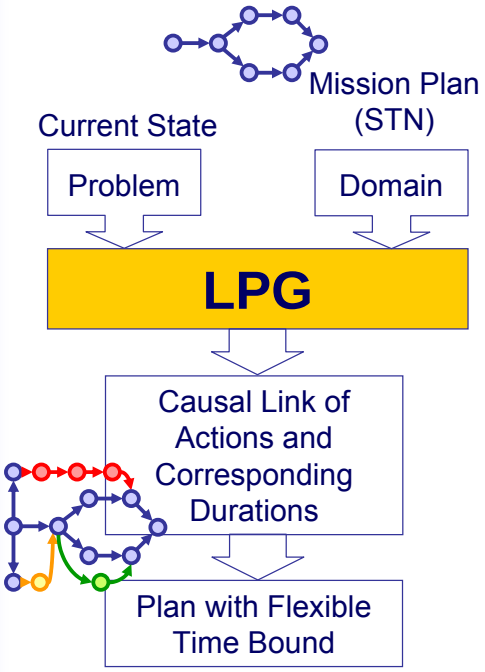
Generative Activity Planner

Uses temporal generative planner (augmented **LPG**) to generate an activity plan from a mission plan

The planner must be able to achieve complex sequence of goals (i.e. a mission plan represented as an STN).

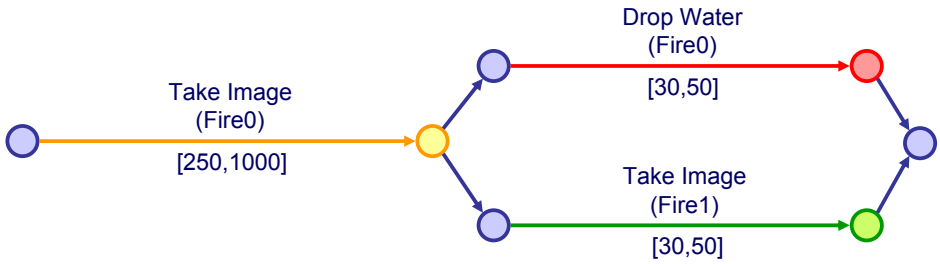


LPG as a Generative Activity Planner



- Dynamic Problem Definition
  - Update current state as necessary
    - Unavailable vehicles
    - Reachable locations
    - Distance between locations
  - Enables closed loop replanning
- Dynamic Domain Definition
  - Add mission plan as domain operators
  - Enables a search for an optimal solution
- Plan with Flexible Time Bound
  - Add upper bound to each actions and check the temporal consistency

Mapping Mission Plan into Domain Operators



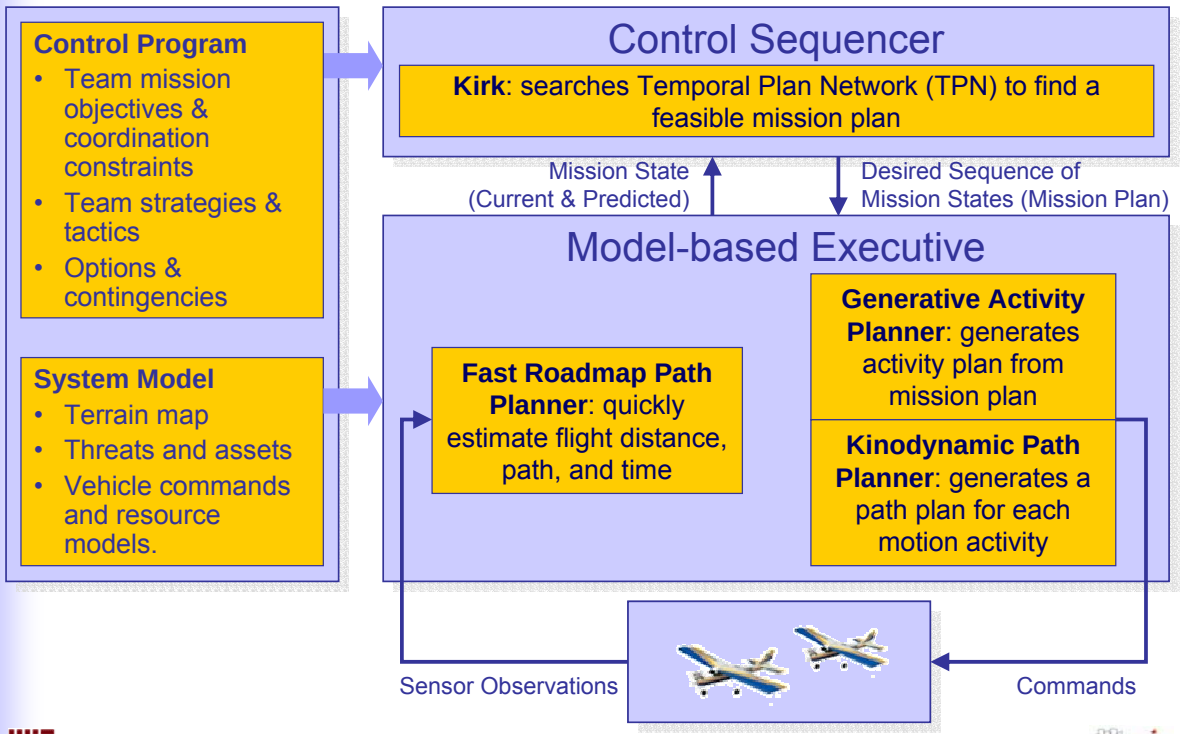

```
(:durative-action take-image-seeker-uav0-fire0
    :parameters ()
    :duration (= ?duration 0)
    :condition (and (at start (not (act0-achieved)))
                    (at start (have-image seeker-uav0 fire0)))
    :effect (at end (act0-achieved)))


(:durative-action drop-water-water-uav0-fire0
    :parameters ()
    :duration (= ?duration 0)
    :condition (and (at start (not (act1-achieved)))
                    (at start (act0-achieved))
                    (at start (at water-uav0 fire0))
                    (at start (dropped-water water-uav0 fire0)))
    :effect (at end (act1-achieved)))
```

Seung's Contributions

1. Wrote the scenario in PDDL2.1 (PDDL+ Level-3 subset)
   - Lack duration inequalities and continuous effects requires many workarounds.
2. Generated a plan for the scenario using LPG
   - Reaching the limits of LPG's capability – required problem description tweeking
3. Develop codes and methods necessary for the proof of concept
   - Gained some insights into a new approach to generative planning
4. Develop/Compile the STN interface necessary for the architecture

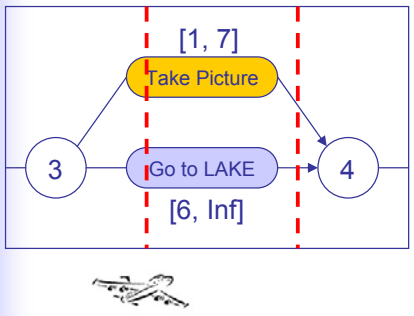
Cooperative Model-based Program Architecture

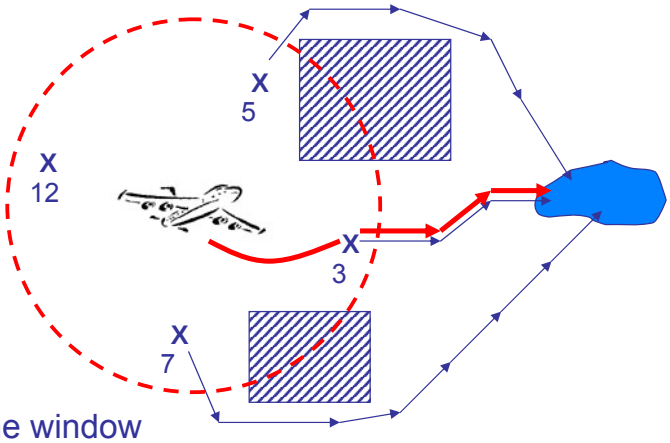


Thomas Leaute's Contributions

1. Wrote a comprehensive software interface with the Cloud Cap simulator, exchanging TCP messages to read telemetry and send commands
2. Created a Tactic-driven Cooperative Path Planner that uses Mixed Integer Linear Programming to both plan paths and execute a temporally flexible activity plan
3. Drafted a receding horizon planning framework that asks the path planner to re-plan any time necessary

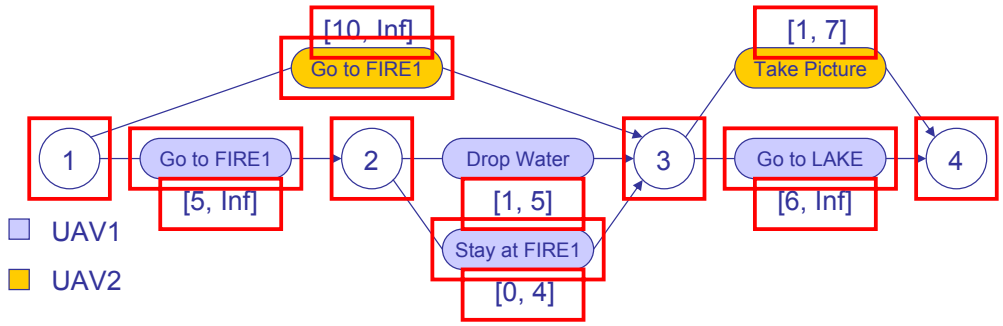
Path Planning within a Receding Horizon Using Mixed Integer Linear Programming





- Only plan within a limited time window
- Use fast roadmap path planner to estimate the remaining cost to go
- **Result**:
  - Quick kinodynamic path planner that minimizes the total path cost
  - Ability to incrementally replan as the knowledge of the environment is updated.

Scheduling within a Receding Horizon Using Mixed Integer Linear Programming



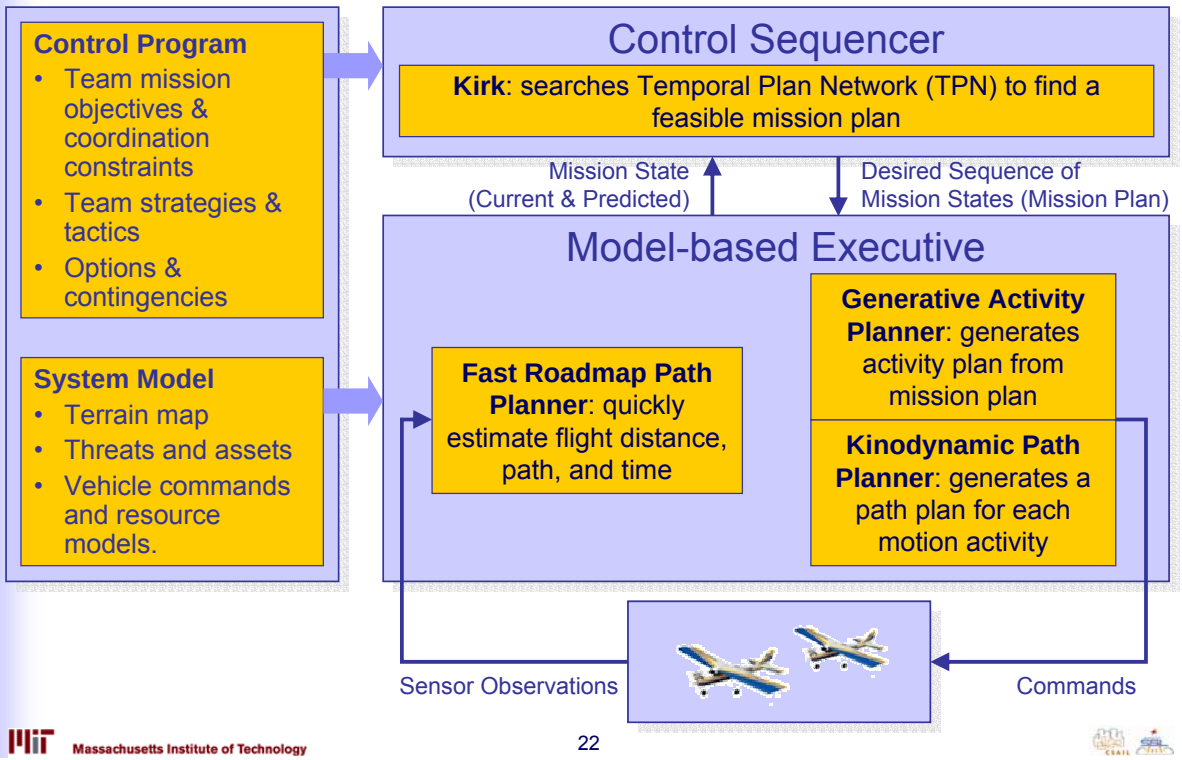
Nodes → time variables t_i

Duration constraints → constraints $T_{min} < t_j - t_i < T_{max}$

"Go to G" activities → post-conditions $X(t_j) = X_G$

"Stay at P" activities → for all $t_i < t < t_j$: $|X(t)-X_P| < e$

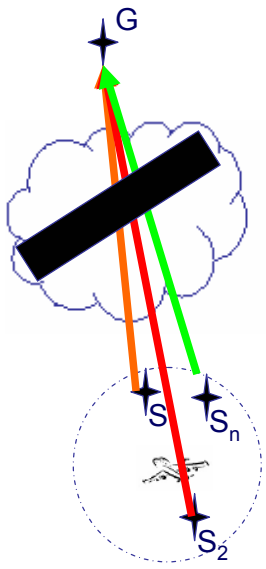
Cooperative Model-based Program Architecture



Dan Lovell's Contribution

- Cost map generating algorithm that uses D*-lite
  - Generate a cost map for a given region
  - Using D*-lite, can respond to dynamic environment using local repair of the path

Generating Cost Maps with D*-lite



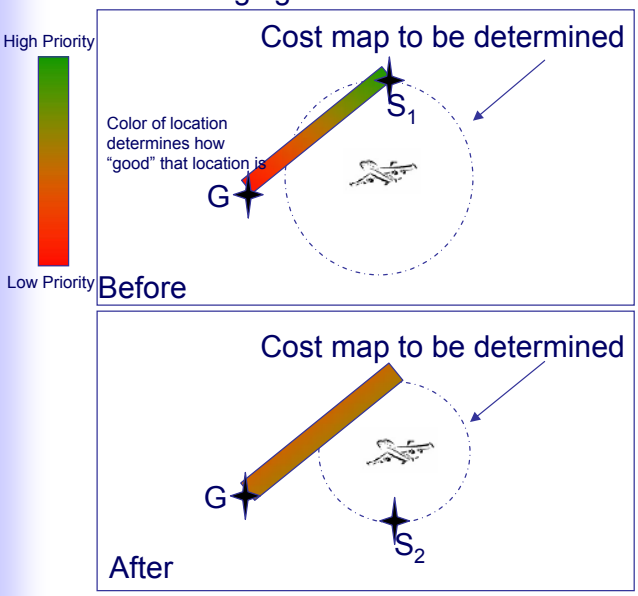
KinoPathPlanner wants to know cost to go for locations inside some radius from its start

To create Cost To Go Map, execute many D*-lite searches to locations in map while saving old state

- Previous consistent nodes remain consistent.
  - Searches to consistent locations terminate immediately.
- Previous priority queue needs to be reordered for each new search location.
  - Reordering priority queue ensures the next search creates consistent nodes.
- How do you prevent too many queue reorderings?
  - Order of searches might matter
  - Change heuristic function or tie breaking so search paths wander more, covering more area near the destination.

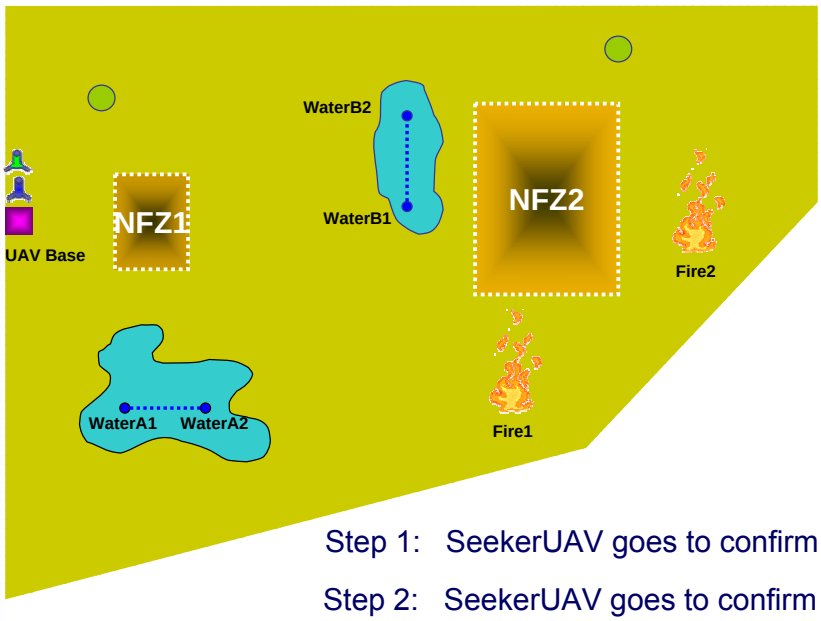
Generating Cost Maps with D*-lite

Depiction of change in Priority Queue after changing search's start locations

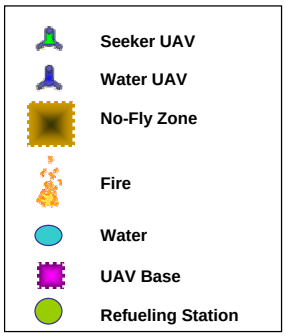


- The order in which you search points in the cost map matters
  - Large changes in euclidean distance between start locations could require much of the priority queue to be reordered
  - Small Changes could cause you to minimally reorder queue but reorder many times since each search wont cover as much new terrain

Cooperative Forest Fire Fighting Scenario



Legend:

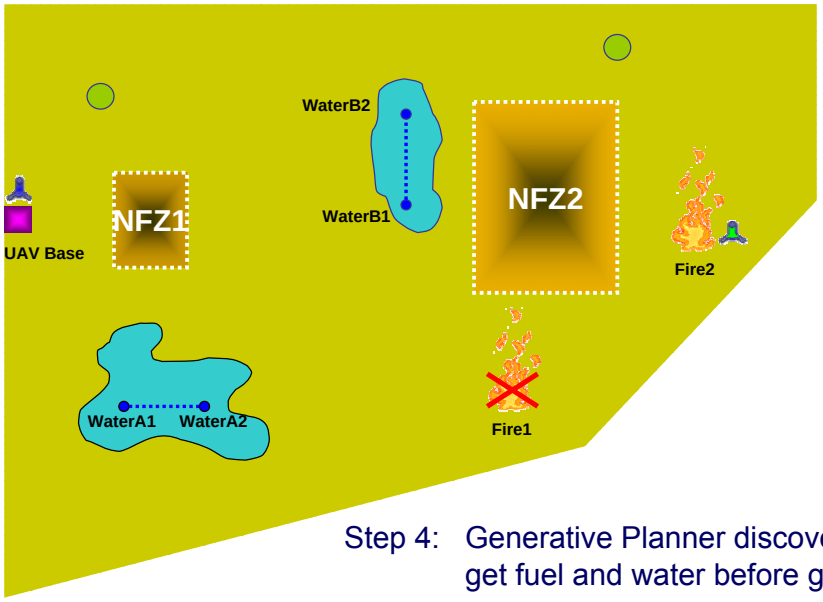


Step 1: SeekerUAV goes to confirm Fire1

Step 2: SeekerUAV goes to confirm Fire2

Step 3: WaterUAV commanded to go and extinguish Fire1

Cooperative Forest Fire Fighting Scenario



Legend:

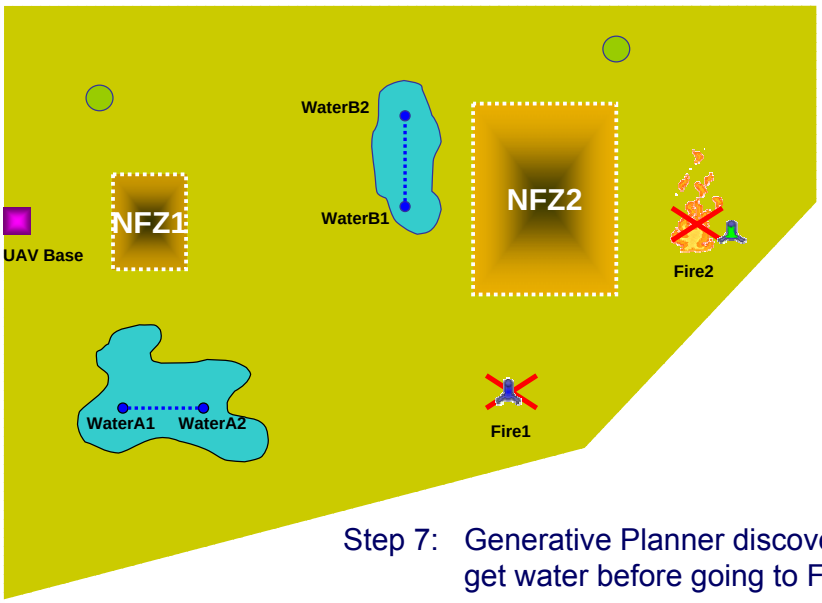
- Seeker UAV
- Water UAV
- No-Fly Zone
- Fire
- Water
- UAV Base
- Refueling Station

Step 4: Generative Planner discovers WaterUAV needs to get fuel and water before going to Fire1

Step 5: WaterUAV drops water on Fire1

Step 6: WaterUAV commanded to go and extinguish Fire2

Cooperative Forest Fire Fighting Scenario



Legend:

- Seeker UAV
- Water UAV
- No-Fly Zone
- Fire
- Water
- UAV Base
- Refueling Station

Step 7: Generative Planner discovers WaterUAV needs to get water before going to Fire2

Step 8: WaterUAV drops water on Fire2

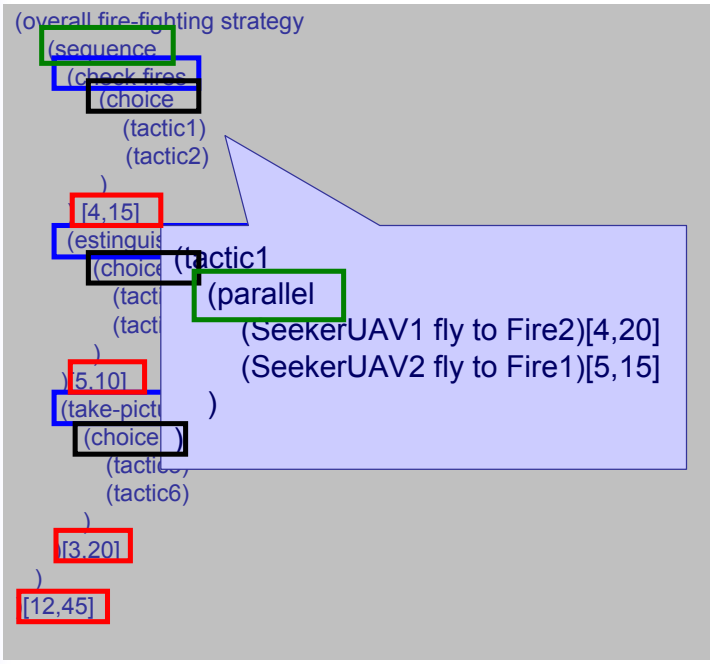
Step 9: SeekerUAV takes pictures of the fire damage

Step 10: UAVs return to Base (and get fuel if needed)

Conclusions

- **Model-based Programming**: Encodes mission strategies or tactics at a simple, intuitive level in terms of intended state evolutions.
- **Dynamic Backtracking**: Quickly generates an optimal mission plan using best-first order or anytime depth first order.
- **Activity Planning on Complex Sequence of Goals**: Refines complex sequence of goals (mission plan) into an actionable activity plan using existing temporal generative planner.
- **Strategy-driven Cooperative Path Planning**: Incorporates a kinodynamic cooperative path planner with the novel ability to design control trajectories specified in temporally flexible plans.
- **Receding Horizon Continuous Planners**: Quickly adapts the optimal plan as the environment and problem are perturbed using road map path planning.

Mission Description in RMPL



Operator inputs detailed mission scenario:

1. Create an overall strategy describing vehicle actions and intended movements.
2. Coordination and timing constraints.
3. Non-Deterministic Choices
4. Concurrent and Sequential Actions

Cooperative Model-based Program Architecture

Model-based Embedded & Robotic Systems

Control Program
- Team mission objectives & coordination constraints
- Team strategies & tactics
- Options & contingencies

System Model
- Terrain map
- Threats and assets
- Vehicle commands and resource models.

Control Sequencer

Kirk: searches Temporal Plan Network (TPN) to find a feasible mission plan

Mission State (Current & Predicted)

Desired Sequence of Mission States (Mission Plan)

Model-based Executive

estimate flight distance, path, and

Generative Activity Planner: generates activity plan from mission plan

Kinodynamic Path Planner: generates a path plan for each motion activity

Cooperative UAV's (Simulated using Cloud Cap Autopilot)

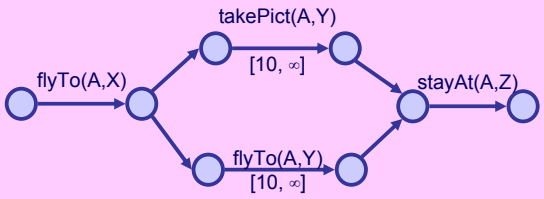
Sensor Observations

Commands

Cooperative Model-based Program Architecture

Model-based Embedded & Robotic Systems

Given high-level mission goals and strategies, selects an optimal sequence of activities from a temporal network with flexible time bounds. (Robert)



Searches a grid map for the shortest paths to specified goals (using D* Lite algorithm)
- Provides the control sequencer and activ planner with lower ti bounds on flight dur
- Allows the kinodyna path planner to plan beyond its receding horizon

(Dan)

Uses temporal generative planner (augmented LPG) to generate an activity plan fro ission plan. (Seung)

Uses Mixed Integer Linear Programming to generate path plans and schedule activities. (Thomas)