Coordinating Agile Systems through the Model-based Execution of Temporal Plans

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Overview of the Presentation

1. Introduction
   - Objective and Challenges
   - Previous Work and Innovations
   - Problem Statement
2. Approach
3. Discussion

1. Introduction

Objective and Challenges

Objective: task-directed coordinated control of agile dynamic systems

- Challenges to address:
  - Under-actuated systems
  - Tight synchronization
  - Robustness to disturbances

1. Introduction

Previous Work

- Challenges to address:
  - Deal with under-actuation
  - Handle tight synchronization
  - Provide robustness

- Previous work:
  - Dispatchable plan execution (Vidal & Ghallab 96, Morris & Muscettola 98, Tsamardinos & Ramakrishnan 03): Scheduling and execution of temporally flexible plans
  - Continuous planning and execution (Ambros-Ingerson & Steel 88, Wilkins & Myers 95, Chien et al. 00): Robust interleaved planning and execution of temporal plans; inspired by Model Predictive Control

1. Introduction

Innovative Claim

- Model-based execution of temporally flexible state plans for continuous, under-actuated systems

- Technical Innovations:
  - Responds to disturbances by framing temporal state plan execution as Model Predictive Control (Propoi 63, Richalet 76, How et al. 02)
  - Achieves real-time performance through novel constraint pruning policies
1. Introduction

Continuous Model-based Execution (CMEx)

- Plant Model
- Temporally Flexible State Plan

Continuous Model-based Executive

- Plant State
- Continuous Controller

Observations

Optimal Control Sequence

Objective Function $F$


2. Approach

Overall Approach

- Receding Horizon CMEx:
  - Solving the full CMEx problem is intractable
  - Iteratively solve smaller versions of the problem

  - Plan up to a small planning horizon $N_t$ (e.g. 25 sec)
  - Execute only up to an execution horizon $n_t$ (e.g. 18 sec) and replan

Receding Horizon CMEx:
- Formulate the problem as a Disjunctive Linear Program (DLP)

Hybrid Controller

- Encode as Disjunctive LP
- Solve up to limited horizon
- Extract Control Sequence

Control Sequences $\{u_0, u_1, u, u_N\}$
2. Approach

Disjunctive Linear Programming (DLP)

- In Conjunctive Normal Form (CNF):
  
  \[
  \text{Minimize } f(x) \\
  \text{Subject to } \bigwedge_{i=1}^{n} \bigvee_{j=1}^{m} g_{ij}(x) \leq c_{ij}
  \]

Example in CNF:

\[
\begin{align*}
\left\{ \begin{array}{c}
x(t) \geq x_E \\
x(t) \leq x_W \\
y(t) \geq y_N \\
y(t) \leq y_S
\end{array} \right. \\
\forall j = 0, N_j
\end{align*}
\]


- In general propositional form:

  \[
  \text{Minimize } f(x) \\
  \text{Subject to } \Phi(x)
  \]

where:

\[
\begin{align*}
\Phi(x) &= \Phi(x) \land \Phi(x) \\
\Phi(x) &= \Phi(x) \lor \Phi(x) \\
\Phi(x) &= \Phi(x) \implies \Phi(x) \\
\Phi(x) &= \Phi(x) \iff \Phi(x) \\
\Phi(x) &= \neg \Phi(x)
\end{align*}
\]

Example in propositional form:

\[
\begin{align*}
\left\{ \begin{array}{c}
x(t) \leq x_W - m \\
\forall j = 0, N_j \implies v_j(t) \leq v_{\max}
\end{array} \right.
\end{align*}
\]


DLP Encodings

- Plant model encodings (cont.):
  - Forbidden regions in the state space (cont.):
    - Bounds on the velocity:

  \[
  \begin{align*}
  v_x &\leq v_{\min} \\
v_y &\leq v_{\min}
  \end{align*}
  \]

- Time constraint between two events \( e_1 \) and \( e_2 \):

  \[
  T(e_2) - T(e_1) \geq \Delta T_{\text{min}} \\
  T(e_2) - T(e_1) \leq \Delta T_{\text{max}}
  \]

Li, H. and Williams, B. C., Efficiently Solving Hybrid Logic/Optimization Problems through Generalized Conflict Learning, ICAPS Workshop “Plan Execution: A Reality Check”, 2005
2. Approach

DLP Encodings

- State plan encodings (cont.):
  - Constraint associated with a \textit{Remain in} activity:

\[
\left\{ \begin{array}{c}
T(e_1) \leq T_0 + t \cdot \Delta t \\
T(e_2) \geq T_0 + t \cdot \Delta t
\end{array} \right\} \implies s(t) \in D
\]

- Guidance constraint for an \textit{End in} activity:

\[
\left\{ \begin{array}{c}
T(e_1) \leq T_0 + (t - 1/2) \cdot \Delta t \\
T(e_2) \geq T_0 + (t + 1/2) \cdot \Delta t
\end{array} \right\} \implies s(t) \in D
\]

2. Approach

Constraint Pruning Policies

- The DLPs can have a very large number of constraints
- Prune part of the search space to reduce the scope of the problem:
  - Spatial search space
  - Temporal search space

2. Approach

Constraint Pruning Policies

- Plant model constraint pruning:
  - Obstacle avoidance constraint pruning
2. Approach

Constraint Pruning Policies

• State plan constraint pruning:
  – Initial graph corresponding to the state plan:
    \[
    [\Delta t_m - \Delta t_m] \\
    \text{Corresponding distance graph}
    \]
  – Run shortest path algorithms to infer absolute time bounds on any event:
    \[
    T_e^{\text{min}} \leq T(e) \leq T_e^{\text{max}}
    \]

Dechter, R., Meiri, I. and Pearl, J., Temporal Constraint Networks, ACC, 1991

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3. Discussion
  • Fire-fighting UAV Demonstration
  • Other examples of Agile Systems
3. Conclusion

Fire-fighting UAV Demonstration

- QuickTime™ and a video decompressor are needed to see this picture.

1. Go to Lake S
2. Fill up water tank
3. Go to Fire S
4. Drop water over fire
5. Go to Lake N
6. Fill up water tank
7. Go to Fuel Station
8. Fill up fuel tank
9. Go to Fire N
10. Drop water over fire
11. Go back to Base

3. Conclusion

Performance Analysis

- Input state plan:
  - 2 vehicles, 2 obstacles,
  - 26 activities,
  - Total execution time of 1300s
- Maintained a planning buffer of 10s

The model-based executive designs optimal control sequences in real-time for horizons < 7.3s. Above 7.3s, the control sequences are sub-optimal.

3. Conclusion

Other Examples of Agile Systems

- Demonstrate the executive on other agile systems:
  - Wheeled exploratory ATRV rovers
  - Arm manipulators performing coordinated assembly tasks

3. Conclusion

Conclusion

- Model-based execution of temporally flexible state plans enables coordination of agile systems.
- Real-time execution is obtained by Model Predictive Control and pruning policies.
- Our executive has been demonstrated on a real-time hardware-in-the-loop UAV testbed.