A Planning Based Framework for Controlling Hybrid Systems

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Outline

Motivation

From Continuous Dynamics...

... to a Domain Model

Domain Predictive Control

Exemplary Simulation

Discussion

Outlook
Motivation

Lunar Lander  ExoMars
Motivation

Think!

acting

goal

sensing

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Motivation

Key Aspects

Hybrid Systems
Continuous Dynamics
Boolean State Variables

Autonomy
Reduction of Computational Effort
Quick Decision Generation

Exogenous Events
Obstacles
Reactivity
Outline

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From a Hybrid System...

Hybrid System

\[ \dot{x}_n(t) = A(x_l) x_n(t) + B(x_l) u(t) \]

Planning Task

Find \( u(t), \ t \in [t_a, t_b] \) such that:

\[ x_n(t_a) \rightarrow x_n(t_b) \]

Initial State \( \rightarrow \) Desired State
…to a Planning Action…

1. Anticipate some input fragments $u_i(t), t \in [0, \delta_i]

2. Solve the differential equations (preprocessing step)

$$\Phi = e^{A(x_i)} \delta_i$$
$$\Psi = \int_{t_0}^{t_0+\delta_i} e^{A(x_i)\cdot(t_0+\delta_i-\tau)} B(x_i) u(\tau) d\tau$$

3. Generate planning action

$$E \vdash x_n(t_0 + \delta_i) = \Phi_i x_n(t_0) + \Psi_i$$
… to the Domain Model

**Domain Model**

- **Action A**
- **Action B**
- **Action C**
- **Action D**
- **Action E**
- **Action F**
- **Action G**

**Planning Problem**

- **Init**
- **Goal**

Graphical representation:

- $x_n$
- $\delta_A$
- $\delta_C$
- $\delta_B$
- $t_0$
- $t_0 + \delta_A$
- $t_0 + \delta_A + \delta_C$
- $t_{end}$

**Goal**

**Init**
Outline

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Outlook
Remember the Key Aspects

- Key Aspects
  - Hybrid Systems
  - Continuous Dynamics
  - Boolean State Variables

- Autonomy
  - Reduction of Computational Effort
  - Quick Decision Generation

- Exogenous Events
  - Obstacles
  - Reactivity
Domain Predictive Control

Initial State

Goal States
Domain Predictive Control

Initial State

Expand limited number of states within Planning Horizon

State with best heuristic information

Goal States
Domain Predictive Control

Initial State

Apply subsequence of actions

State with best heuristic information

Goal States
Domain Predictive Control

Initial State

Expand limited number of states within Planning Horizon

State with best heuristic information

Goal States
Domain Predictive Control

Initial State

State with best heuristic information

Goal States

Apply subsequence of actions

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Domain Predictive Control

Initial State

Expand limited number of states within Planning Horizon

Solution found

Goal States
Domain Predictive Control

- **Key Aspects**
  - Hybrid Systems
  - Continuous Dynamics
  - Boolean State Variables
  - Autonomy
  - Reduction of Computational Effort
  - Quick Decision Generation

**Exogenous Events**
- Obstacles
- Reactivity
Domain Predictive Control

Sensors, FDI, etc. → new environment or system knowledge → Replanning

update

Domain Model

action A
action B
action C
action D
action E
action F
action G
action H

Nominal Action
Faulty Action

Planning Problem

init
e.g. unmodeled disturbances
e.g. changes of the environment

goal

updated state
original state
Domain Predictive Control Architecture

```
user --> s_0
\quad k = 0

Problem
\quad s_{k+1} = s_k

Domain

Planner

Plan

Interpreter

u_l(t) --> Plant Logic
\quad \dot{x}_l(t)

Estimator

\hat{x}(t)

Plan

\dot{x}_n(t) \rightarrow f
\quad x_n(t)

Plant

\dot{x}_n(t) \rightarrow B(x_l)
\quad u_n(t)

A(x_l)

C(x_l)

y_n(t)

\mathbf{t} \in [t_k, t_{k+c}]
```

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- Discussion
- Outlook

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Exemplary Simulation

<table>
<thead>
<tr>
<th>Action</th>
<th>$\alpha_y$</th>
<th>$\alpha_x$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0°</td>
<td>0°</td>
</tr>
<tr>
<td>1</td>
<td>0°</td>
<td>2.92°</td>
</tr>
<tr>
<td>2</td>
<td>0°</td>
<td>−2.92°</td>
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<tr>
<td>3</td>
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<td>5</td>
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<td>6</td>
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<td>7</td>
<td>2.92°</td>
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</tr>
<tr>
<td>8</td>
<td>−2.92°</td>
<td>−2.92°</td>
</tr>
</tbody>
</table>

$\delta_i = 0.5 \, s, \forall \, i \in [0,8]$
Exemplary Simulation

Planned States
Simulated Trajectory
Intermediate Promising Trajectory
Outline

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Planner Performance

Model Accuracy

Suitable Heuristics

Fine Grain Discretization

Computing Power

Number of Anticipated Input Fragments
### Summary and Conclusion

#### Pros
- **general** problem formulation
- **changing system configurations**
- restricted state space
- **failure tolerance**

#### Cons
- anticipated input fragments
- discrete system dynamics
- computational effort
- currently: linear systems only
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- American Institute of Aeronautics and Astronautics Astrodynamics Specialist Conference (August 2012)
  “Planning-based Autonomous Lander Control”
  J. Löhr, B. Nebel, and S. Winkler
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Heuristic

Error State Heuristic

\[ h = \| e_p + e_v \|_1 \]

Open Heuristic Issues:
1. Weighting of numerical variables
2. Weighting between numerical and logical variables
Stable Dynamics

Homogeneous Solution of Stable Dynamics

\[ \dot{x}_n(t) = A_{cl}x_n(t) + Bu_n(t) \]

\( A_{cl} \) state feedback controlled

\[ u_n(t) = -Kx_n(t) \]

closed loop dynamics

\( A_{cl} = A - BK \)

choose controller \( K \) such that

\[ Re(eig[A - BK]) < 0 \]
Stable Dynamics

Homogeneous Solution of Stable Dynamics

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closed loop dynamics
\( A_{cl} = A - BK \)

choose controller \( K \) such that
\( \text{Re}(\text{eig}|A - BK|) < 0 \)

Feasible state feedback control region (actuator saturations!)
Discretized Dynamics

$x_1$

Homogeneous Solution $\Phi_1$

$x_2$
Discretized Dynamics

Homogeneous Solution $\Phi_1$

+ Inhomogeneous Solution $\Psi$
Discretized Dynamics

Homogeneous Solution $\Phi_2$ of Changed Dynamics
Discretized Dynamics

Homogeneous Solution $\Phi_2$ of Changed Dynamics

$\begin{align*}
x_1 \\
x_2
\end{align*}$
The Domain Model
A Piecewise Affine System?

\[ x_n(k + 1) = \Phi_i x_n(k) + \Psi_i , \quad x_n \in \Omega_i \]

\[ \Omega_i \cap \Omega_j = \emptyset, \quad \forall \ i \neq j \]

\( \mathcal{X} : \) is not necessarily empty, we explicitly allow for overlaps of \( \Omega_i \) Depicts the state space we can choose between actions
Time Discretization

\[ x_n \]

\[ s^* \]

\[ \text{obstacle} \]

\[ \delta_A \]

\[ \delta_C \]

\[ \delta_B \]

\[ t_0 \]

\[ t_0 + \delta_A \]

\[ t \]