Timeline-based Planning:Theory and Practice
Planning Domains and Non-Flexible Timelines

LOGICA PER L'INFORMATICA

–

Maggio, 2020
Universita' degli Studi ROMA TRE

Context & Motivations

- Planning for real world problems with explicit temporal constraints is a challenging problem

- Flexible timeline-based Planning and Scheduling $(\mathrm{P\&S})$ has demonstrated to be successful in a number of concrete applications

- A remarkable research effort has been dedicated to design, build and deploy timeline-based software environments

- Nevertheless, a formal characterization of flexible timelines and flexible plans was missing

- A rather limited community put efforts to make research in this area

A Running Example: the Satellite Planning Domain

- A generic Planning problem in space domain
- A remote satellite is controlled by a planner and an executive system to accomplish some required tasks
- The satellite can either point to
  - a remote planet using its instruments to produce scientific data
  - an Earth ground communication station downlinking the scientific data previously stored
- A set of operative constraints are to be satisfied:
  - Point the planet to allow observations
  - Point Earth to transmit data to ground station
  - Communicate only if ground station is visible
  - Perform some maintenance operations

Planning Domains

Timeline based planning: synthesis of desired temporal behaviors (timelines) of time varying features (state variables)

The domain specification contains causal laws and constraints that must be obeyed:

- allowed value transitions
- durations of valued intervals
- constraints (synchronization) between different state variables
- information on intervals controllability/uncontrollability

The desired temporal behaviour includes satisfaction of given goals

Planning Domains

Timeline based planning: synthesis of desired temporal behaviors (timelines) of time varying features (state variables)

The domain specification contains causal laws and constraints that must be obeyed:

- allowed value transitions
- durations of valued intervals
- constraints (synchronization) between different state variables
- information on intervals controllability/uncontrollability

The desired temporal behaviour includes satisfaction of given goals

In general, time instants and durations are elements of an infinite set of non negative numbers $\mathbb{T}$, including 0

For instance, $\mathbb{T} = \mathbb{N}$ (discrete time framework), or $\mathbb{T} = \mathbb{R}_{\geq 0}$, the non-negative real numbers

$$\mathbb{T}^{\infty} = \mathbb{T} \cup \{\infty\}$$

State Variables

$$x = (V, T, \gamma, D)$$

- x: variable name
- V: set of values
- $T : V \rightarrow 2^V$: value transition function
- $\gamma : V \rightarrow \{c, u\}$: controllability tagging function

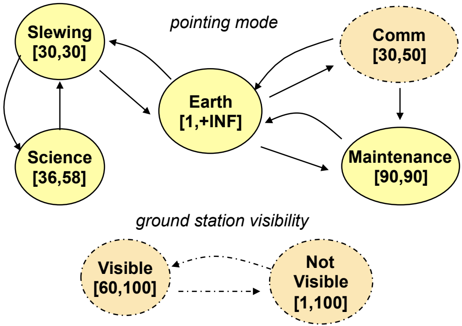
  $\gamma(v)$: controllability tag of the value v.

  $\gamma(v) = u$: v is an uncontrollable value
  (the controller cannot decide its exact duration)

  $\gamma(v) = c$: v is controllable
- $D : V \rightarrow \mathbb{T} \times \mathbb{T}^\infty$: duration function ; $D(v) = (t_{min}, t_{max})$, with $0 \leq t_{min} \leq t_{max}$

Example

The "pointing mode" and"ground station visibility" state variables



The exact duration of the intervals with values **Communication**, **Visible** and **Not Visible** is uncontrollable.

The *Ground station visibility* variable is external.

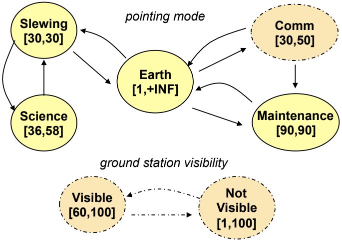
State Variables

$$pm = (V, T, \gamma, D)$$

- $V = \{Earth, Comm, \dots\}$
- $T(Earth) = \{Comm, Slewing, \dots\}$
  $T(Comm) = \{Earth\}, \dots$
- $\gamma(Comm) = u$,
  $\gamma(v) = c$ for the other values
- $D(Earth) = (1, \infty)$,
  $D(Slewing) = (30, 30), \dots$

$$gv = (V', T', \gamma', D')$$

- $V' = \{Visible, NotVisible\}$,
- $T'(Visible) = \{NotVisible\}$,
  $T'(NotVisible) = \{Visible\}$
- $\gamma(Visible) = \gamma(NotVisible) = u$
- $D'(Visible) = (60, 100)$,
  $D'(NotVisible) = (1, 100)$



Temporal Relations

- Temporal relations between intervals $A = [s_A, e_A]$ and $B = [s_B, e_B]$

$A \leq^{start,start}_{[lb,ub]} B$	A starts between lb and ub time units before B starts ($lb \leq s_B - s_A \leq ub$)
$A \leq^{end,end}_{[lb,ub]} B$	A ends between lb and ub time units before B ends ($lb \leq e_B - e_A \leq ub$)
$A \leq^{start,end}_{[lb,ub]} B$	A starts between lb and ub time units before B ends ($lb \leq e_B - s_A \leq ub$)
$A \leq^{end,start}_{[lb,ub]} B$	A ends between lb and ub time units before B starts ($lb \leq s_B - e_A \leq ub$)

Temporal Relations

- Temporal relations between intervals $A = [s_A, e_A]$ and $B = [s_B, e_B]$

$A \leq^{start,start}_{[lb,ub]} B$	A starts between lb and ub time units before B starts ($lb \leq s_B - s_A \leq ub$)
$A \leq^{end,end}_{[lb,ub]} B$	A ends between lb and ub time units before B ends ($lb \leq e_B - e_A \leq ub$)
$A \leq^{start,end}_{[lb,ub]} B$	A starts between lb and ub time units before B ends ($lb \leq e_B - s_A \leq ub$)
$A \leq^{end,start}_{[lb,ub]} B$	A ends between lb and ub time units before B starts ($lb \leq s_B - e_A \leq ub$)

Allen's qualitative temporal relations can be defined

Temporal Relations

- Temporal relations between intervals $A = [s_A, e_A]$ and $B = [s_B, e_B]$

$A \leq_{[lb,ub]}^{start,start} B$	A starts between lb and ub time units before B starts ($lb \leq s_B - s_A \leq ub$)
$A \leq_{[lb,ub]}^{end,end} B$	A ends between lb and ub time units before B ends ($lb \leq e_B - e_A \leq ub$)
$A \leq_{[lb,ub]}^{start,end} B$	A starts between lb and ub time units before B ends ($lb \leq e_B - s_A \leq ub$)
$A \leq_{[lb,ub]}^{end,start} B$	A ends between lb and ub time units before B starts ($lb \leq s_B - e_A \leq ub$)

Allen's qualitative temporal relations can be defined

- Temporal relations between an interval $A = [s, e]$ and a timepoint t

$A \leq_{[lb,ub]}^{start/end} t$	A starts/ends between lb and ub time units before t
$A \geq_{[lb,ub]}^{start/end} t$	A starts/ends between lb and ub time units after t

Synchronization Rules

Examples

- An operational requirement: the satellite communicates with the Earth only when the ground station is visible (communication is "contained" in visibility)
- A known fact: at the beginning, the satellite is pointing to Earth

Synchronization Rules

Examples

- An operational requirement: the satellite communicates with the Earth only when the ground station is visible (communication is "contained" in visibility)
- A known fact: at the beginning, the satellite is pointing to Earth

In general

$$a_0[x_0 = v_0] \to \exists\, a_1[x_1 = v_1] \ldots a_n[x_n = v_n] \,.\mathcal{C}$$
$$\top \to \exists\, a_1[x_1 = v_1] \ldots a_n[x_n = v_n] \,.\mathcal{C}$$

Formulae: positive boolean formulae (PBFs) made up of "atoms" (temporal relations where intervals are replaced by token variables)

Synchronization Rules

Examples

- An operational requirement: the satellite communicates with the Earth only when the ground station is visible (communication is "contained" in visibility)
- A known fact: at the beginning, the satellite is pointing to Earth

In general

$$a_0[x_0 = v_0] \rightarrow \exists\, a_1[x_1 = v_1] \ldots a_n[x_n = v_n]\,.\mathcal{C}$$
$$\top \rightarrow \exists\, a_1[x_1 = v_1] \ldots a_n[x_n = v_n]\,.\mathcal{C}$$

Formulae: positive boolean formulae (PBFs) made up of "atoms" (temporal relations where intervals are replaced by token variables)

$$a_0[pm = Comm] \quad \rightarrow \quad \exists\, a_1[gv = Visible]\,.a_1 \leq^{start,start}_{[0,\infty]} a_0 \wedge a_0 \leq^{end,end}_{[0,\infty]} a_1$$

$(a_1$ contains $a_0)$

$$\top \quad \rightarrow \quad \exists a_1[pm = Earth].\ a_1 \leq^{start}_{[0,0]} 0$$

Planning Domains and Goals

- Planning Domain $\mathcal{D} = (SV, \mathcal{S})$
  - SV is a set of state variables (partitioned into planned and external state variables)
  - $\mathcal{S}$ is a set of synchronization rules

- Goal $\mathcal{G} = (\Gamma, \Delta)$
  - $\Gamma = \{g_1 = (x_1, v_1), \ldots, g_n = (x_n, v_n)\}$ (there exist intervals g_i where the variable x_i has the value v_i)
  - Δ (relational goal) is a PBF where only the token variables $g_1, \ldots g_n$ occur (the formula Δ holds for the intervals given in Γ)

  $\mathcal{G}$ is represented by the synchronization rule

$$S_{\mathcal{G}} = \top \rightarrow \exists\, g_1[x_1 = v_1] \ldots g_n[x_n = v_n].\Delta$$

Example: $\Gamma = \{g_1 = (pm, Science), g_2 = (pm, Maintenance)\}$
$\Delta = (g_1 \text{ meets } g_2) \vee (g_1 \text{ before } g_2)$

Planning Problems

- Planning Problem $(\mathcal{D}, \mathcal{G}, H)$
  - $\mathcal{D}$ is a planning domain
  - $\mathcal{G}$ is a planning goal for $\mathcal{D}$
  - $H \in \mathbb{T}$ is the planning horizon
- When external variables are present, a planning problem also contains an observation, i.e. the information available to the planner about their behavior (details in Cialdea Mayer & Orlandini & Umbrico, ACTA INFORMATICA 2016)

Non-flexible Timelines in a Controllable Context

Let $x = (V, T, D)$ be a state variable
(now ignoring the controllability tagging function)

- Token for x:

$$x^j = (v, d) \quad \text{for } j \in \mathbb{N},\ v \in V,\ d \in D(v)$$

  v is the token value: $value(x^j)$; d is its duration: $duration(x^j)$

- Timeline for x

$$TL_x = x^0 = (v_0, d_0), x^1 = (v_1, d_1), \ldots, x^k = (v_k, d_k)$$

  where $x^0, \ldots, x^k$ are tokens for x

  - e_k is the temporal horizon of TL_x.
  - once a token x^i is embedded in a timeline, its start and end times can be easily computed:

$$start\_time(x^i) = \sum_{j=0}^{i-1} d_j \qquad end\_time(x^i) = start\_time(x^i) + d_i$$

Non-flexible Plans

- A Plan for the state variables in SV is a set of timelines

$$\mathbf{TL} = \{TL_{x_1}, \ldots, TK_{x_k}\}$$

where $SV = \{x_, \ldots, x_k\}$

The plan horizon H is the minimum among the temporal horizons of $TL_{x_1}, \ldots, TL_{x_k}$.

TL describes the behavior of each state variable in SV *at least* within the time point H.

- **TL** is a solution plan for the problem $\mathcal{P} = (\mathcal{D}, \mathcal{G}, H')$ if
  - it is valid w.r.t. $\mathcal{D} = (SV, \mathcal{S})$, i.e. it satisfies all the synchronizations in $\mathcal{S}$,
  - it satisfies the synchronization rule representing $\mathcal{G}$,
  - $H \geq H'$ and
  - all the goals are fulfilled before H'

A Non-flexible Plan

- An example of non flexible plan for the satellite planning domain
- two timelines (pointing mode and ground station visibility)