Temporal Planning in Space

based on:

“Application of Mapgen to MER,”
by Kanna Rajan

“Handling Time: Constraint-based Interval Planning,”
by David E. Smith

Brian C. Williams and
Robert Morris (guest lect.)
16.412J/6.834J
March 2nd, 2005
Outline

- Operational Planning for the Mars Exploration Rovers
- Review of Least Commitment Planning
- Constraint-based Interval Planning
- Temporal Constraint Networks
- Temporal Constraints with Preference

Based on slides by Dave Smith, NASA Ames
Mission Objectives:

- Learn about ancient water and climate on Mars.
- For each rover, analyze a total of 6-12 targets
  - Targets = natural rocks, abraded rocks, and soil
- Drive 200-1000 meters per rover
Mars Exploration Rover
Surface Operations Scenario

Day 1
Long-Distance Traverse
(<20-50 meters)

Day 2
Initial Position;
Followed by
"Close Approach"

Day 2 Traverse Estimated Error Circle

Day 2 Traverse Estimated Error Circle

Day 2 Traverse Estimated Error Circle

Day 2 Traverse Estimated Error Circle

Day 3
Science Prep
(if Required)

Day 4
During the Day
Science Activities

During the Day
Autonomous On-
Board Navigation
Changes, as needed
One day in the life of a Mars rover

Courtesy: Jim Erickson
MAPGEN: Automated Science Planning for MER

Planning Lead: Kanna Rajan (ARC)

EUROPA Automated Planning System

Sequence Build

Science Team

Flight Rules
Engineering
Resource Constraints
Science
Navigation
DSN/Telcom

Satellite Dish
Next Challenge: Mars Smart Lander (2009)

Mission Duration: 1000 days
Total Traverse: 3000-69000 meters
Meters/Day: 230-450
Science Mission: 7 instruments, sub-surface science package (drill, radar), in-situ sample “lab”
Technology Demonstration: (2005).
Course Challenge: 16.413 Fall 03

• What would it be like to operate MER if it was fully autonomous?

Potential inspiration for course projects:

• Demonstrate an autonomous MER mission in simulation, and in the MIT rover testbed.
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Planning

Find:

program of actions that achieves the objective
Find:

**program of actions that achieves the objective**

- partially-ordered set
- typically unconditional

goals
Paradigms

Classical planning
(STRIPS, operator-based, first-principles)
“generative”

Hierarchical Task Network planning
“practical” planning

MDP & POMDP planning
planning under uncertainty
The Classical Representation

**Initial Conditions:** $P_1, P_2, P_3, P_4$

**Operators:**
- $pre_1$
- $pre_2$
- $pre_3$
- $Op$
- $eff_1$
- $eff_2$

**Goals:** $Goal_1, Goal_2, Goal_3$
Simple Spacecraft Problem

Observation-1
  target
  instruments

Observation-2

Observation-3

Observation-4

...

pointing

calibrated
Example

16.410/13: Solved using Graph-based Planners (Blum & Furst)
Some STRIPS Operators

TakeImage (?target, ?instr):
   Pre: Status(?instr, Calibrated), Pointing(?target)
   Eff: Image(?target)

Calibrate (?instrument):
   Pre: Status(?instr, On), Calibration-Target(?target), Pointing(?target)
   Eff: ¬Status(?inst, On), Status(?instr, Calibrated)

Turn (?target):
   Pre: Pointing(?direction), ?direction ≠ ?target
   Eff: ¬Pointing(?direction), Pointing(?target)
1. Select an open condition
2. Choose an op that can achieve it
   Link to an existing instance
   Add a new instance
3. Resolve threats
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Based on slides by Dave Smith, NASA Ames
An Autonomous Science Explorer

Objective:
maximize science return

Observation-1
priority
time window
target
instruments
duration

Observation-2

Observation-3

Observation-4

…

Based on slides by Dave Smith, NASA Ames
Complications

Objective: maximize science return

- Observation-1
  - priority
  - time window
  - target
  - instruments
  - duration

- Observation-2
- Observation-3
- Observation-4
... - consumables:
  - fuel
  - power
  - data storage
  - cryogen

- angle between targets
  ⇒ turn duration

- calibration
  - target1
  - target2
  ...

Based on slides by Dave Smith, NASA Ames
Limitations of Classical Planning with Atomic Actions (aka STRIPS)

- Instantaneous actions
- No temporal constraints
- No concurrent actions
- No continuous quantities
Needed Extensions

Time
Resources
Utility
Uncertainty
World Description

State-centric (Mc Carthy):
for each time describe propositions that are true

History-based (Hayes):
for each proposition describe times it is true

Based on slides by Dave Smith, NASA Ames
Representing Timing: Qualitative Temporal Relations [Allen AAAI83]

A before B

A meets B

A overlaps B

A contains B

A = B

A starts B

A ends B

Based on slides by Dave Smith, NASA Ames
Representing Temporal Operators:
TakelImage Schema

TakelImage (?target, ?instr):
Pre: Status(?instr, Calibrated), Pointing(?target)
Eff: Image(?target)

TakelImage (?target, ?instr)
  contained-by Status(?instr, Calibrated)
  contained-by Pointing(?target)
  meets Image(?target)

Based on slides by Dave Smith, NASA Ames
Pictorially

Based on slides by Dave Smith, NASA Ames
TakelImage Schema Semantics

TakelImage (?target, ?instr)

-contained-by Status(?instr, Calibrated)
-contained-by Pointing(?target)
-meets Image(?target)

\[\Rightarrow \exists P \{\text{Status}(?\text{instr}, \text{Calibrated})_P \land \text{Contains}(P, A)\} \]
\[\land \exists Q \{\text{Pointing}(?\text{target})_Q \land \text{Contains}(Q, A)\} \]
\[\land \exists R \{\text{Image}(?\text{target})_R \land \text{Meets}(A, R)\} \]

Based on slides by Dave Smith, NASA Ames
Turn

Turn (?target) met-by meets Pointing(?direction)

Based on slides by Dave Smith, NASA Ames
Calibrate

Calibrate (?instr)
met-by Status(?instr, On)
contained-by CalibrationTarget(?target)
contained-by Pointing(?target)
meets Status(?instr, Calibrated)
A Temporal Planning Problem

- Past
  - Pointing(Earth)
  - Status(Cam1, Off)
  - Status(Cam2, On)
  - CalibrationTarget(T17)

- Future
  - Image(??target)

Based on slides by Dave Smith, NASA Ames
A Consistent Complete Temporal Plan
CBI Planning Algorithm

Choose:

- introduce an action & instantiate constraints
- coalesce propositions

Propagate constraints
Initial Plan

Past

- Pointing(Earth)
- Status(Cam1, Off)
- Status(Cam2, On)
- CalibrationTarget(T17)

Future

Image(?target)

Based on slides by Dave Smith, NASA Ames
Expansion 1

Based on slides by Dave Smith, NASA Ames
Coalescing

Based on slides by Dave Smith, NASA Ames
Relation to Causal Links & Threats

Causal links:

POCL

CBI

Threats:

Based on slides by Dave Smith, NASA Ames
# Examples of CBI Planners

<table>
<thead>
<tr>
<th>Planners</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zeno (Penberthy)</td>
<td>intervals, no CSP</td>
</tr>
<tr>
<td>Trains (Allen)</td>
<td></td>
</tr>
<tr>
<td>Descartes (Joslin)</td>
<td>extreme least commitment</td>
</tr>
<tr>
<td>IxTeT (Ghallab)</td>
<td>functional rep.</td>
</tr>
<tr>
<td>HSTS (Muscettola)</td>
<td>functional rep., activities</td>
</tr>
<tr>
<td>EUROPA (Jonsson)</td>
<td>functional rep., activities</td>
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Based on slides by Dave Smith, NASA Ames
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- Operational Planning for the Mars Exploration Rovers
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- Temporal Constraint Networks
- Model-based Program Execution as Graph-based Temporal Planning
Qualitative Temporal Constraints  
(Allen 83)

- x before y
- x meets y
- x overlaps y
- x during y
- x starts y
- x finishes y
- x equals y
- y after x
- y met-by x
- y overlapped-by x
- y contains x
- y started-by x
- y finished-by x
- y equals x
Example: Deep Space One Remote Agent Experiment

Based on slides by Dave Smith, NASA Ames
Qualitative Temporal Constraints
Maybe Expressed as Inequalities
(Vilain, Kautz 86)

- x before y \( X^+ < Y^- \)
- x meets y \( X^+ = Y^- \)
- x overlaps y \( (Y^- < X^+) \text{ & } (X^- < Y^+) \)
- x during y \( (Y^- < X^-) \text{ & } (X^+ < Y^+) \)
- x starts y \( (X^- = Y^-) \text{ & } (X^+ < Y^+) \)
- x finishes y \( (X^- < Y^-) \text{ & } (X^+ = Y^+) \)
- x equals y \( (X^- = Y^-) \text{ & } (X^+ = Y^+) \)

Inequalities may be expressed as binary interval relations:
\( X^+ - Y^- < [-\text{inf}, 0] \)
Metric Constraints

• Going to the store takes at least 10 minutes and at most 30 minutes.
  → $10 \leq [T^+(store) – T^-(store)] \leq 30$

• Bread should be eaten within a day of baking.
  → $0 \leq [T^+(baking) – T^-(eating)] \leq 1\text{ day}$

• Inequalities, $X^+ < Y^-$, may be expressed as binary interval relations:
  → $-\infty < [X^+ - Y^-] < 0$

Based on slides by Dave Smith, NASA Ames
Metric Time: Quantitative Temporal Constraint Networks
(Dechter, Meiri, Pearl 91)

• A set of time points $X_i$ at which events occur.

• Unary constraints

\[(a_0 \leq X_i \leq b_0) \text{ or } (a_1 \leq X_i \leq b_1) \text{ or } \ldots\]

• Binary constraints

\[(a_0 \leq X_j - X_i \leq b_0) \text{ or } (a_1 \leq X_j - X_i \leq b_1) \text{ or } \ldots\]
Temporal Constraint Satisfaction Problem (TCSP)

\[ < X_i, T_i, T_{ij} > \]

- \( X_i \) continuous variables
- \( T_i, T_{ij} \) interval constraints
  \[ \{I_1, \ldots, I_n \} \text{ where } I_i = [a_i, b_i] \]
  - \( T_i = (a_i \leq X_i \leq b_i) \text{ or } \ldots \text{ or } (a_i \leq X_i \leq b_i) \)
  - \( T_{ij} = (a_1 \leq X_i - X_j \leq b_1) \text{ or } \ldots \text{ or } (a_n \leq X_i - X_j \leq b_n) \)

[Dechter, Meiri, Pearl, aij89]
TCSP Are Visualized Using Directed Constraint Graphs
Simple Temporal Networks:

- A set of time points $X_i$ at which events occur.
- Unary constraints
  
  \[
  (a_0 \leq X_i \leq b_0) \text{ or } (a_1 \leq X_i \leq b_1) \text{ or } \ldots
  \]
- Binary constraints
  
  \[
  (a_0 \leq X_j - X_i \leq b_0) \text{ or } (a_1 \leq X_j - X_i \leq b_1) \text{ or } \ldots
  \]

Sufficient to represent:
- most Allen relations
- simple metric constraints

Can’t represent:
- Disjoint activities
Simple Temporal Network

- $T_{ij} = (a_{ij} \leq X_i - X_j \leq b_{ij})$
A Completed Plan Forms an STN

**Thrust Goals**
- Delta_V(direction=b, magnitude=200)

**Power**

**Attitude**
- Point(a)
- Turn(a,b)
- Point(b)
- Turn(b,a)

**Engine**
- Off
- Warm Up
- Thrust (b, 200)
- Off

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A Completed Plan Forms an STN

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