Network-Aware Automated Planning and Plan Execution

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Motivation

April 2009:
- 75% of coalition force casualties in Afghanistan are from roadside bombs.
- 40% of coalition force casualties in Iraq are from roadside bombs.

Source: Tom Vanden Brook, USA Today

Motivating Scenario

- IED Detection.
- Monitor Locations.
- Techniques.
- Actors.
- Resources.
- Evaluators.

Heterogeneous Network
multiple different network technologies are combined to work together simultaneously.

Network-Centric System
a distributed system where performance is dependent on the quality of the underlying network communication links.
Contributions

- Qualitatively-different plans:
  - Generating plans over a range of evaluation criteria;
  - Visualizing plan evaluations.
  - Improve plan selection.
- Network-Aware Agents:
  - Classical planning domains for distributed service composition;
  - Measuring the performance and effectiveness of planning, execution, and monitoring agents;
  - Incorporating network-awareness.

Service Composition to Automated Planning

Definition

"Service composition is the linking… of existing services so that their aggregate behavior is that of a desired service (the goal)" [Hoffmann et al. 09].

- Requires Semantic Web Services [Sirin et al. 04].
- QoS Assurance [Gu et al. 03].

Assumes static networking.

Agents in Planning

Agents:

- Planning Agent.
- Execution Agent.
- Monitoring Agent.

[Tate 93]

Planning Under Uncertainty

Restrictive Assumptions:

- Determinism.
- Full observability.
- Reachability goals.

[Nau et al. 04]

Sources of Uncertainty:

- Partial observability.
- Unreliable resources.
- Measurement variance.
- Inherently vague concepts.
Fault Detection & Isolation (FDI)

Types of FDI:
- Analytic.
- Data-driven.
- Knowledge-based.

[Pettersson 05]

Approach

1. Modify planner to improve the quality of the plans it produces based on evaluation criteria.
2. Add network-awareness to planning, execution, and monitoring agents.

Purpose
To improve network-centric automated planning and execution.

Formal Problem Statement

\( \Sigma \) is the planning domain — the model of the world passed as input to the planner.

\( \Sigma \) is a Tuple
- \( S \) set of states;
- \( A \) set of actions;
- \( E \) set of events;
- \( \gamma \) transition function \( \gamma : S \times A \rightarrow S \).

Formal Problem Statement

The functions on planning actions:

- \( \text{precond}(a) \) preconditions of \( a \);
- \( \text{effects}^+(a) \) positive effects of \( a \);
- \( \text{effects}^-(a) \) negative effects of \( a \);
- \( \text{host}(a) \) the single host \( h \) from \( a \);
- \( \text{resources}(a) \) the set of resources (parameters) of action \( a \).
The planning agent receives the tuple, $I_P$, and creates a set of plans, $P_I$. $I_P$ is a Tuple

- $\Sigma$: automated planning domain;
- $s_0$: initial state;
- $S_g$: set of goal state(s);
- $H$: set of hosts (nodes) on the network;
- $\omega_H$: host link weighting.

**Problem**

To find and execute $p_I \in P_I$ where $p_I = \{a_0, a_1, \ldots, a_{|p_I|}\}$ and execution of $p_I$ yields the best domain-dependent and network-centric evaluations.

**Network-Awareness**

An agent exhibits network-awareness if changes to $\omega_H$ cause the agent's output to change while all other inputs remain constant.
Formal Problem Statement

Planning Domain Extensions

Operator distribution
- e.g., NODE1ACTION(parameters)
- Implicit constraints.

Resource distribution
- e.g., ACTION(node1, parameters)

Complexity
- Operator distribution increases the number of actions in $\Sigma$ to $|H| \times |A|$ in the worst case.
- Resource distribution increases the number of constraints in the world-state.

Planning Agents

Agent Types:
- Domain-Independent.
- Random.
- Guided.

Plan Evaluators:
- Steps.
- Alternatives.
- Longest temporarily ordered path.
- Duplicate plans.
- (none).
- IED detection accuracy.
- Plan execution time.
- Network link quality.
- Network bandwidth usage.
**Domain-Independent Planning Agent**

- Uses I-Plan’s default strategy.

**I-Plan**

University of Edinburgh, Tate et al.’s plan-space HTN planner which is built on an intelligent agent framework, I-X.

**Process**

- Traverses search space depth-first.
- Encounters an alternative whose constraints cannot be satisfied.
- Backtracks using an A* search.

**Random Planning Agent**

- DFS with random branching.

```java
CONSTRUCTRANDOMPLAN(I)
1: toVisit.push(s0)
2: while ¬toVisit.empty ∧ ¬solution(toVisit.peek()) do
3: v ← toVisit.pop()
4: if v /∈ visited then
5: visited.add(v)
6: r ← randomize(v.children)
7: toVisit.push(r)
8: end if
9: end while
10: return toVisit.peek()
```

**Guided Planning Agent**

Generates qualitatively-different plans over:
- Domain-dependent criteria, and
- Network-centric criteria.

**Process**

- A priority queue exists for each evaluator.
- Every partial-plan is evaluated by all evaluators and placed in their respective priority queues.
- The partial-plan at the head of each priority queue is used for the next step.
Guided Planning Agent

Planning Agent
Evaluator 1
Evaluator 2
Evaluator 3
Evaluator 4

Execution Agents

Agent types:
- Naive
- Reactive
- Proactive

Defined by:
- Service invocation
- Error handling

Naive Execution Agent

Naive Execution Agent Properties
Service Invocation: Invokes services exactly as described by $p_I$.

The naive agent requires that
$$\forall a \in p_I, host(a) \neq \emptyset \land resources(a) \neq \emptyset$$

Error Handling: Ignores execution errors.

- Not network-aware
Reactive Execution Agent Properties

Service Invocation: Invokes services exactly as described by \( p_I \).

- The reactive agent requires that \( \forall a \in p_I, \text{host}(a) \neq \emptyset \wedge \text{resources}(a) \neq \{\} \).

Error Handling: Repairs the failed \( p_I \) by replacing failed service call(s) with new ones, creating \( p'_I \).

- Network-aware recovery — plan repair.
- Uses routing protocol neighbors & link quality.

Proactive Execution Agent Properties

Service Invocation: Invokes services using network-aware logic to choose the host and resources at execution time. The proactive execution agent uses only service descriptions from actions \( a \in p_I \), meaning \( \forall a \in p_I, \text{host}(a) = \emptyset \wedge \text{resources}(a) = \{\} \).

Error Handling: Repairs the failed \( p_I \) by replacing failed service call(s) with new ones, creating \( p'_I \).

- Network-aware host/resource grounding.
Monitoring Agents

Methods of FDI
- Analytic. — Active Monitor
- Data-driven. — Passive Monitor
- Knowledge-based.

Analytic Monitoring Agent

Given the ordered plan \( p_I = \{ a_0, a_1, \ldots, a_n \} \)

An analytic monitoring agent:
- Constructs \( p_M = \{ m_0, m_1, \ldots, m_n + 1 \} \), an ordered set of monitoring actions;
- Creates the new execution plan \( p'_I = \bigcup_{i=0}^{n} \{ m_i, a_i \} \);
- The result is \( p'_I = \{ m_0, a_0, m_1, a_1, \ldots, m_n, a_n, m_{n+1} \} \).

Each \( m \in p_M \) calculates the residual between expected and actual bytes transferred.

Data-driven Monitoring Agent

Execution Agent

Faults

Data-driven Monitoring Agent 1

Data-driven Monitoring Agent 2

Data-driven Monitoring Agent n

Faults
Data-driven Monitoring Agent

- Multivariate monitor.
- Data packets.
- Retransmission timeouts.

Plan Evaluation Criteria Statistics

**Aspects**
- Range (effective and theoretic).
- Direction (minimize or maximize).
- Statistics (e.g., mean, median, mode, standard deviation).

**Benefit**
Plans can be positioned along an absolute continuum of evaluation values.

Dominant Plans

**Definition**
A plan, $p$, is dominant to a set of other plans, $P^-$, in respect to two or more plan evaluators $e_1, ..., e_k \in E$ when
$$\forall e \in E, p \in P^- \iff [e(p) \geq e(p^-)].$$

Plan Evaluation Visualization
### Plan Evaluation Benchmarking

#### Action Providing Hosts
- PHYSICALMOVE all
- ACQUIRECAMERA all
- TAKEPHOTO all
- GETOLDPHOTO all
- RELEASECAMERA all
- CHECKFORIEDAT 1, 2, and 5
- MANUALSEARCH 1, 2, 3, and 4
- PHOTOGRAPHICSEARCH 3, 4, and 5
- PHOTOARCHIVE 5
- PHOTOCOMPARE 4 and 5
- RESULTREPORT 2 and 5

#### Camera Resolution

<table>
<thead>
<tr>
<th>Camera</th>
<th>Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Camera 1</td>
<td>3.2 MP</td>
</tr>
<tr>
<td>Camera 2</td>
<td>8.0 MP</td>
</tr>
</tbody>
</table>

#### Node Speed (max mph) Transportation Cost ($ per mile)

<table>
<thead>
<tr>
<th>Node</th>
<th>Speed (max mph)</th>
<th>Transportation Cost ($ per mile)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Node 1</td>
<td>30</td>
<td>6.0</td>
</tr>
<tr>
<td>Node 2</td>
<td>40</td>
<td>6.5</td>
</tr>
<tr>
<td>Node 3</td>
<td>20</td>
<td>5.1</td>
</tr>
<tr>
<td>Node 4</td>
<td>10</td>
<td>4.9</td>
</tr>
<tr>
<td>Node 5</td>
<td>45</td>
<td>6.2</td>
</tr>
</tbody>
</table>

### Plan Evaluation Benchmarking Results

Each planning algorithm ran in I-Plan for five minutes.

#### Plan Evaluations

<table>
<thead>
<tr>
<th></th>
<th>Bandwidth</th>
<th>IED Acc.</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>I-Plan Default</td>
<td>0.949</td>
<td>0.759</td>
<td>291.4</td>
</tr>
<tr>
<td>Random</td>
<td>1.647</td>
<td>1.476</td>
<td>177.9</td>
</tr>
<tr>
<td>Guided</td>
<td>1.916</td>
<td>1.141</td>
<td>392.6</td>
</tr>
</tbody>
</table>

#### Dominant Plans

<table>
<thead>
<tr>
<th>Search Strategy</th>
<th>% Dominant Plans Produced</th>
</tr>
</thead>
<tbody>
<tr>
<td>I-Plan Default</td>
<td>7.4%</td>
</tr>
<tr>
<td>Random</td>
<td>53.3%</td>
</tr>
<tr>
<td>Guided</td>
<td>59.3%</td>
</tr>
</tbody>
</table>
### Experiment: Network-Aware Agent Combinations

<table>
<thead>
<tr>
<th>Agent</th>
<th>Technique</th>
</tr>
</thead>
<tbody>
<tr>
<td>Planning</td>
<td>Random</td>
</tr>
<tr>
<td></td>
<td>Domain-independent (I-Plan)</td>
</tr>
<tr>
<td>Execution</td>
<td>Naive</td>
</tr>
<tr>
<td></td>
<td>Reactive</td>
</tr>
<tr>
<td></td>
<td>Proactive</td>
</tr>
<tr>
<td>Monitoring</td>
<td>Data-driven</td>
</tr>
<tr>
<td></td>
<td>Analytic</td>
</tr>
<tr>
<td></td>
<td>(none)</td>
</tr>
</tbody>
</table>

### Experimental Setup
- Multi-objective Optimization (MOO) Function.
- Implemented agents with I-X and I-Plan.
- Network emulation.
- Mobility models.

**MOO function**

\[
\text{MOO}(p_I) = \text{IEDDetectAcc}(p_I) + 3 \times \text{TranspCost}(p_I) + 5 \times \text{ExecTime}(p_I) + \text{LinkQuality}(p_I) + \text{BandwidthUse}(p_I)
\]

### CORE
- Boeing’s Common Open Research Emulator.
- FreeBSD network stack emulation.
- Simple Multicast Forwarding (SMF).
- Open Shortest Path First (OSPF).

### Mobility Models
- **Purpose**
  - Dictate geographical node locations.
  - Dynamic \( \omega_2 \).

- **Mobility Patterns**
  - Local.
  - Static.
  - Dynamic.
  - Partition-merge.
Mobility Models

Purpose
- Dictate geographical node locations.

Mobility Patterns
1. Local.
2. Static.
3. Dynamic.

Domain-independent Plan

Random Plan
Guided Plan

```plaintext
checkForIEDAt location1 photographicSearch node5 location1
physicalMoveToCamera node5 camera2
acquireCamera node5 location1 camera2
physicalMove node5 location1 getOldPhoto node5 to photo-0
takePhoto node5 location1 camera2 to photo-1
comparePhotos node5 photo-1 photo-0
reportResults node5 location1
checkForIEDAt location2
manualSearch node3 location2
physicalMove node3 location2
conductScan node3 location2
physicalMove node5 location2
reportResults node5 location2
checkForIEDAt location3
manualSearch node4 location3
physicalMove node4 location3
conductScan node4 location3
physicalMove node2 location3
reportResults node2 location3
```

Local Results: Mean Time

- Network not a factor.
- Network-awareness did not hurt.

Local Results: Mean IED Detection Accuracy

- Ideal values of IED detection accuracy.

Planning Agent Comparison

- Network disruptions adversely effect plan execution times.
  - Guided was 16.7% faster than I-Plan and 28.8% faster than random in part-merge.
Execution Agent Effectiveness

Planning Agent: domain-independent (I-Plan default)
- Naïve agent has the lowest IED detection accuracy and exec. time.
- Reactive and proactive agents achieved ideal IED detection accuracies.

Execution Agent Effectiveness

Planning Agent: random
- Naïve agent failed most often.
- Proactive agent finished considerably faster than reactive.

Execution Agent Effectiveness

Planning Agent: guided (network-aware)
- Naïve agent failed most often.
- The guided algorithm advice significantly helped the execution agent.

Execution Agent Performance
- Proactive agent uses slightly more network transmissions under connected mobility patterns.
- Under part-merge, the proactive agent sent fewer than half as many packets as the reactive agent.
Monitoring Agent Comparisons

**Analytic Monitoring Agent**
- High percentage of false-positives.
- Communication errors — incorrect residuals.
- Active monitor.
- Analytic monitors are less-suitable for network-centric domains.

**Data-driven Monitoring Agent**

Normal execution:

![Graph showing data-driven monitoring agent performance during normal execution.]

Network disconnection:

![Graph showing data-driven monitoring agent performance during network disconnection.]

- In 54 trials...
  - 9.25% false-positives (type I error).
  - 1.85% false-negatives (type II error).
Main Contributions

- Qualitatively-different plan generation:
  - Qualitatively different plans over a range of plan evaluation criteria.
  - Visualizing plan evaluations.
- Network-aware agents:
  - Network-aware planning agents.
  - Network-aware execution agents.
  - Network-aware monitoring agents.

Future Work

- Knowledge-based monitoring agents.
- Incorporate the effects of planning actions into heuristics.

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- Evan Sultanik

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IED Detection Accuracy and Bandwidth Usage

[Graph depicting IED Detection Accuracy vs. Network Bandwidth Usage]
Network Hops and Execution Time

Plan Evaluation Benchmarking Execution Time Distribution

Plan Evaluation Benchmarking IED Detect. Acc. Distribution

Plan Evaluation Benchmarking Link Quality Distribution