A Framework for Plan Library Evolution in BDI Agent Systems

Mengwei Xu, Kim Bauters, Kevin McAreavey, Weiru Liu
Extending BDI with FPP


Extend existing BDI to account for incomplete plan library by synthesising new plans using FPP at runtime.
Extending BDI with Evolving Plan Library

Programming-Based
Belief-Desire-Intention (BDI)

Model-Based
Hierarchical Task Networks (HTN)
First-Principles Planning (FPP)

Learning-Based
Reinforcement Learning

Reusable FPP plans
Expansion and contraction of plan library
- Plan Library Expansion
  -- Syntactical and ad-hoc
- No works on Plan Library Contraction
CAN: Agent \((\mathcal{B}, \Lambda, \Pi)\)

- **Initial belief base**
  - Belief base specifying agent’s initial beliefs

- **Action description library**
  - Set of STRIPS-style action descriptions

- **Plan library**
  - Set of plan rules
CAN: Agent ($\mathcal{B}, \Lambda, \Pi$)

Initial belief base
Belief base specifying agent’s initial beliefs

Belief base $\mathcal{B} \subseteq \mathcal{L}$
Set of formulas from logical language $\mathcal{L}$

$\mathcal{B}$ must support:
- $\mathcal{B} \models \varphi$ (Entailment)
- $\mathcal{B} \cup \{\varphi\}$ (Addition)
- $\mathcal{B} \setminus \{\varphi\}$ (Deletion)

Assume $\mathcal{B}$ is a set of atoms
CAN: Agent \((\mathcal{B}, \Lambda, \Pi)\)

Action description library
Set of STRIPS-style action descriptions

**Action description** \(\text{act} : \varphi \leftarrow \mathcal{B}^- ; \mathcal{B}^+\)

- Primitive action symbol
- Precondition \(\varphi \in \mathcal{L}\)
- Set of "add" atoms \(\mathcal{B}^+ \subseteq \mathcal{L}\)
- Set of "delete" atoms \(\mathcal{B}^- \subseteq \mathcal{L}\)
CAN: Agent \((\mathcal{B}, \Lambda, \Pi)\)

**Plan library**

Set of plan rules

**Context** \(\varphi \in \mathcal{L}\)

Formula from \(\mathcal{L}\)

**Plan rule** \(e : \varphi \leftarrow P\)

**Triggering event** \(e\)
e.g. belief update, new (sub)goal

**Body (program)** \(P \ ::= \text{nil} | \text{act} | ? \varphi | + b | - b | ! e | P_1 ; P_2 | P_1 \triangleright P_2 | P_1 \parallel P_2 | \text{goal}(\varphi_s, P, \varphi_f) | \text{goal}(\varphi_s, \varphi_f)\)

Empty program

Entailment

Belief deletion

Sequencing

Concurrency

CAN declarative goal

Pure declarative goal

Primitive action

Belief addition

New (sub)goal

Conditional
CAN: Operational Mechanism Sketch

Triggering event \( e \)
e.g. belief update, new (sub)goal

\[ e : \varphi_1 \leftarrow P_1 \]
\[ e : \varphi_2 \leftarrow P_2 \]
\[ e : \varphi_3 \leftarrow P_3 \]
\[ \vdots \]
\[ e : \varphi_n \leftarrow P_n \]

\( \subseteq \Pi \)

Relevant Plans

\[ e : \varphi_{11} \leftarrow P_{11} \]
\[ e : \varphi_{21} \leftarrow P_{21} \]
\[ e : \varphi_{31} \leftarrow P_{31} \]
\[ \vdots \]
\[ e : \varphi_{n1} \leftarrow P_{n1} \]

Applicable Plans

where \( \mathcal{B} = \varphi_j, j \in \{1, \ldots, n\} \)
Our Plan Library Evolution Framework in BDI

1. Introduce Domain-independent Characteristics of a Plan Library
   • **Activeness** (i.e. how often plans are used)
   • **Success** (i.e. how well plans have performed)
   • **Functionality** (i.e. how many types of triggering events/goals it can respond to)
   • **Robustness** (i.e. how easy it is to replace a plan when it does not work)

2. Present Principle Definition of a Plan Library Evolution Framework
   • Postulates of a plan library *expansion operation*
   • Postulates of a plan library *contraction operator*
   • None-functionality and robustness decreasing *theorem to plan library expansion operator*
   • Set operation properties *theorem to plan library contraction operator*

3. Instantiate Plan Library Contraction Operator
   • **Employ** multi-criteria argumentation-based decision making
   • **Prove** such specific contraction operator satisfies the postulates
Measuring Performance of Plan

\[ S: \mathcal{P} \times \mathcal{T} \rightarrow \{1, \bot, \emptyset\} \]

\textbf{Status function}
- plans
- timestamps
- success
- failure
- undefined (e.g. still under execution)

\textbf{Execution frequency:}
\[ \Delta(P, t_1, t_2) = |\{S(P, t_i) \neq \emptyset \cdot i = 1, 2, \cdots, n\}| \]

1. overall execution frequency
2. latest execution frequency

\textbf{Success rate:}
\[ \Phi(P, t_1, t_2) = \frac{\Delta^s(P, t_1, t_2)}{\Delta(P, t_1, t_2)} \]

where \( \Delta^s(P, t_1, t_2) = |\{S(P, t_i) \neq 1 \cdot i = 1, 2, \cdots, n\}| \)
Relationships between Plans

Recall: \( \mathcal{P} \) is a set of plans and \( e^P = \{ e : \varphi_1 \leftarrow P_1, e : \varphi_2 \leftarrow P_2, \ldots, e : \varphi_n \leftarrow P_n \} \) is a set of relevant plans to respond to triggering event \( e \)

**Relevancy:** \( \Upsilon_P(P) = |e^P| - 1 \)

**Replaceability:** \( \Gamma_P(P) = |S \cdot P \succ_{mr} S| \)

where \( P \succ_r S = \{ P_1, P_2, \ldots, P_n \} \)

iff.
1. overlapping possible world \( \mathcal{O}(P_1, P_2, \ldots, P_n) \neq 0 \)
2. post-effects subsuming holds \( \text{post}(P_1, P_2, \ldots, P_n) \models \text{post}(P) \)

where \( P \succ_{mr} S = \{ P_1, P_2, \ldots, P_n \} \)

iff.
1. \( P \succ_r S \)
2. \( P \not\succ_{r} S \setminus P' \) for \( \forall P' \in S \)
Summary Information for a Plan Library

Execution frequency: \( \Delta(\Pi, t_1, t_2) = \frac{\sum_{P \in \Pi} \Delta(P, t_1, t_2)}{|\Pi|} \)
Success rate: \( \Phi(\Pi, t_1, t_2) = \frac{\sum_{P \in \Pi} \Delta^S(P, t_1, t_2)}{|\Pi|} \)
Functionality: \( F(\Pi) = |\{ e \cdot e^P \in \Pi\} | \)
Relevancy: \( \Upsilon_P(P) \) where \( P = \Pi \)
Replaceability: \( \Gamma_P(P) \) where \( P = \Pi \)

Domain-independent Characteristics Orderings

\( \{\succeq_{activity}, \succeq_{success}, \succeq_{functionality}, \succeq_{robustness}\} \)

- \( \Pi \succeq_{activity} \Pi' \) iff \( \Delta(\Pi, t_1, t_2) \geq \Delta(\Pi', t_1, t_2) \)
- \( \Pi \succeq_{success} \Pi' \) iff \( \Phi(\Pi, t_1, t_2) \geq \Phi(\Pi', t_1, t_2) \)
- \( \Pi \succeq_{functionality} \Pi' \) iff \( F(\Pi) \geq F(\Pi') \)
- \( \Pi \succeq_{robustness} \Pi' \) iff \( \forall P \in \Pi \) s.t. \( P \in \Pi' \), \( \Upsilon_\Pi(P) \leq \Upsilon_{\Pi'}(P) \), \( \Gamma_\Pi(P) \leq \Gamma_{\Pi'}(P) \)
Plan Library Expansion

Plan Library Expansion Operator

Given a plan library $\Pi$ and a plan $P$, $\Pi \circ P$ denotes the expansion of $\Pi$ by $P$ with $\circ$ if and only if it satisfies the following postulates:

- **EO1** $\Pi \circ P$ is a plan library.
- **EO2** $P \in \Pi \circ P$ and $\Pi \subseteq \Pi \circ P$.
- **EO3** if $P \in \Pi$, then $\Pi \circ P = \Pi$.
- **EO4** $(\Pi \circ P) \circ P' = (\Pi \circ P') \circ P$.

**Proposition:** $\Pi \circ \{P, P'\} = (\Pi \circ P) \circ P' = (\Pi \circ P') \circ P$

**Theorem:** $\Pi \circ P \succ_{functionality} \Pi$ and $\Pi \circ P \succ_{robustness} \Pi$

the number of types of triggering event relevancy and replaceability
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EO4 $(\Pi \circ P) \circ P' = (\Pi \circ P') \circ P$.

Proposition: $\Pi \circ \{P, P'\} = (\Pi \circ P) \circ P' = (\Pi \circ P') \circ P$

Theorem: $\Pi \circ P \gtrsim_{\text{functionality}} \Pi$ and $\Pi \circ P \gtrsim_{\text{robustness}} \Pi$

the number of types of triggering event

relevancy and replaceability

Union $\cup$

\[ e : \varphi_1 \leftarrow P_1 \]
\[ e : \varphi_2 \leftarrow P_2 \]
\[ e : \varphi_3 \leftarrow P_3 \]
\[ \vdots \]
\[ e : \varphi_n \leftarrow P_n \]

?CONFLICT

\[ e : \varphi' \leftarrow P' \]
Plan Library Contraction (Cont.)

Plan Library Contraction Operator

Given a plan library \( \Pi \), \( \mathcal{V}(\Pi) \) denotes the contraction of \( \Pi \) by \( \mathcal{V} \) iff it satisfies the following postulates:

1. \( \mathcal{V}(\Pi) \) is a plan library.
2. \( \mathcal{V}(\Pi) \subseteq \Pi \).
3. If \( \mathcal{P} \subseteq \Pi \setminus \mathcal{V}(\Pi) \) and \( \mathcal{P} \subseteq \Pi' \subseteq \Pi \), then \( \mathcal{P} \subseteq \Pi' \setminus \mathcal{V}(\Pi') \).
4. \( \mathcal{V}(\Pi) \trianglerighteq \Pi \) where \( \trianglerighteq \in \{ \trianglerighteq_{activeness}, \trianglerighteq_{success} \} \).
5. \( \forall \mathcal{P} \in \Pi \setminus \mathcal{V}(\Pi) \), then \( \Gamma_{\mathcal{V}(\Pi)}(\mathcal{P}) > 0 \).

Set Properties of contraction operator \( \mathcal{V} \)

1. \( \mathcal{V}(\Pi') \subseteq \mathcal{V}(\Pi) \) if \( \Pi' \subseteq \Pi \). \hspace{1cm} \text{ordered set inclusion}
2. \( \mathcal{V}(\Pi \cap \Pi') \subseteq \mathcal{V}(\Pi) \cap \mathcal{V}(\Pi') \). \hspace{1cm} \text{intersection set inclusion}
3. \( \mathcal{V}(\Pi \setminus \Pi') \subseteq \mathcal{V}(\Pi) \setminus \mathcal{V}(\Pi') \). \hspace{1cm} \text{difference set inclusion}
4. \( \mathcal{V}(\Pi \cup \Pi') \subseteq \mathcal{V}(\Pi) \cup \mathcal{V}(\Pi') \). \hspace{1cm} \text{union set inclusion}
Plan Library Contraction (Cont.)

Plan Library Contraction Operator

Given a plan library $\Pi$, $\nabla(\Pi)$ denotes the contraction of $\Pi$ by $\nabla$ iff it satisfies the following postulates:

- **CO1** $\nabla(\Pi)$ is a plan library.
- **CO2** $\nabla(\Pi) \subseteq \Pi$.
- **CO3** if $\mathcal{P} \subseteq \Pi \setminus \nabla(\Pi)$ and $\mathcal{P} \subseteq \Pi' \subseteq \Pi$, then $\mathcal{P} \subseteq \Pi' \setminus \nabla(\Pi')$.
- **CO4** $\nabla(\Pi) \triangleright= \Pi$ where $\triangleright= \in \{\triangleright=\text{activeness,} \triangleright=\text{success}\}$.
- **CO5** $\forall P \in \Pi \setminus \nabla(\Pi)$, then $\Gamma_{\nabla(\Pi)}(P) > 0$.

Set Properties of contraction operator $\nabla$

1. $\nabla(\Pi') \subseteq \nabla(\Pi)$ if $\Pi' \subseteq \Pi$. ordered set inclusion
2. $\nabla(\Pi \cap \Pi') \subseteq \nabla(\Pi) \cap \nabla(\Pi')$. intersection set inclusion
3. $\nabla(\Pi \setminus \Pi') \subseteq \nabla(\Pi) \setminus \nabla(\Pi')$. difference set inclusion
4. $\nabla(\Pi \cup \Pi') \subseteq \nabla(\Pi) \cup \nabla(\Pi')$. union set inclusion
Plan Library Contraction (Cont.)

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**CO4** $\nabla(\Pi) \succeq \Pi$ where $\succeq \in \{\succeq_{activeness}, \succeq_{success}\}$.

**CO5** $\forall P \in \Pi \setminus \nabla(\Pi)$, then $\Gamma_{\nabla(\Pi)}(P) > 0$.

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ordered set inclusion
intersection set inclusion
difference set inclusion
union set inclusion
Plan Library Contraction

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\[\Pi \cap \Pi' \quad \nabla(\Pi) \quad \nabla(\Pi')\]
Plan Library Contraction

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Practical Results: Instantiation of Contraction Operator $\nabla$

$\nabla^{abm} = \Omega(\langle X, C, \succ_C, R \rangle)$

- Multi-criteria argumentation-based decision making contraction operator
- Selected candidates of decision problem
  - $X = \{P \in \mathcal{P} | \Gamma_{\mathcal{P}}(P) > 0, C_4(P) < \tau\}$
- $C = \{C_1, C_2, C_3, C_4\}$
  - $\succ_C = \{(C_4, C_3), (C_2, C_1), (C_4, C_2), (C_3, C_1)\}$

Replaceability Filtering to protect the fragility

Latest success rate Tolerance

Overall execution frequency

Overall success rate

Latest execution frequency
Theoretical Results: Satisfiability of Contraction Operator $\nabla^{abm}$

$\nabla^{abm} = \Omega(\langle X, C, >_C, R \rangle)$ is indeed a contraction operator satisfying $\textbf{CO1}$–$\textbf{CO5}$

\textbf{CO1} $\nabla(\Pi)$ is a plan library. \hspace{10cm} \text{HOLDS}

\textbf{CO2} $\nabla(\Pi) \subseteq \Pi$. \hspace{10cm} \text{HOLDS}

\textbf{CO3} if $\mathcal{P} \subseteq \Pi \setminus \nabla(\Pi)$ and $\mathcal{P} \subseteq \Pi' \subseteq \Pi$, then $\mathcal{P} \subseteq \Pi' \setminus \nabla(\Pi')$. \hspace{10cm} \text{HOLDS}

\textbf{CO4} $\nabla(\Pi) \geq \Pi$ where $\geq \in \{\geq_{activity}, \geq_{success}\}$. \hspace{10cm} \text{HOLDS}

\textbf{CO5} $\forall P \in \Pi \setminus \nabla(\Pi)$, then $\Gamma_{\nabla(\Pi)}(P) > 0$. \hspace{10cm} \text{HOLDS}
Summary:

1. One of the very first works which challenges the static nature of plan library in BDI agent system.

2. One of the works which proposed clear domain-independent characteristics of the plan library and corresponding measures.
   - Useful for Agent Validation Development
   - Useful for Agent Programming Development
   - Useful for Agent Reasoning Development

3. A non-trivial combination of recent techniques (e.g., measuring literature and multi-criteria decision making) based on useful concepts in BDI.

4. The first work which suggests some desirable properties of plans to formalize plan library modifications in BDI agent systems.
Future Work:

Intention Progression In BDI Agent System: A Formal Approach (targeting AAMAS2019)

1. **Formalise** intention as decomposition-history graph

2. **Tackle** interleaved deliberation of concurrent intentions

3. **Propose** quantitative approach i.e. urgency of goals, preference of plans, awards of actions

4. **Manage** uncertainty arising from non-determinism (e.g. stochastic effects of actions)

5. **Support** anytime manner (i.e. online planning via Monte-Carlo Tree Search)
Questions?

Thank you