Technical Report

A Formal Description of the <I-N-OVA> Model

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1 The <I-N-OVA> Constraint Model of Plans

A plan is represented as a set of constraints of three principal types. To reflect the three main types of constraint identified and their differentiation in the model, the constraint set for a plan is written as <I-N-OVA> (Issues - Nodes - Orderings/Variables/Auxiliary).

The <I-N-OVA> representation of plans sits aside from any use of those plans (generation, refinement, communication, repair, analysis, etc) so that plans and plan fragments can be passed between any systems components or agents that look at, use or manipulate plans. The plan is in a form that is separate to and not dependent on any specific data structures inside the agents, components, planners, etc.

An <I-N-OVA> description defines a space of legitimate plan elaborations within a given plan space that could be reached by arbitrary combination of the actions available in the domain model (i.e. using the domain's action library, plan case library, or partial plan library).

<I-N-OVA> is a tuple of sets of constraints. A legitimate plan elaboration must respect each constraint in each set within the <I-N-OVA> tuple.

N – a set of "include node n" constraints. This states that node n must be included in a legitimate plan elaboration.

A node may represent an action, a step of the plan, etc.

Each node n has an associated unique label.

Each node is associated with two time points "begin n" and "end n".

O – a set of constraints on time points.

These may be pairwise constraints on the distance between two time points, but the general model is not limited to this.

V – a set of constraints on any (variable) entities referred to within the plan.

These are co-designation and non-codesignation (and perhaps other) constraints on entities referred to within the plan.

A – Auxiliary (or other) constraints.

These may be stated with respect to zero, one (time point constraints), two (time range constraints) or multiple time points.

In particular, auxiliary constraints are used in formal models today to represent condition/effect world state teleological requirements.

Depending on the problem domain constraints that are important, we have found it useful to classify these constraints into the following sub-types

- Authority
- World Conditions/Effects
- Resources

- Other (e.g. spatial)

This fits well with models from other fields (cf. IDEF and R-Charts).

I – a set of "issues" (or implied constraints) relating to the plan that must be "addressed" in a legitimate plan elaboration. These may include unsatisfied world conditions, abstract actions/nodes to be expanded, condition/effect interactions to be resolved, etc.

1.1 <N-OVA> and <I-N-OVA>

<N-OVA> is very similar to Hendler and Khabhampati's <T, O, B, ST, L> tuple formalisation of plans (see for example [4]).

Hierarchical versions of <N-OVA> are the most common form of representation used in planners like NOAH, Nonlin and SIPE–2 .

"I" constraints are often hidden in the control structure of planners and scheduling systems where they may appear as interaction lists, data structures constraining the results of running plan analysis critics, etc.

Early descriptions of O-Plan used the term "flaw" for the list of issues and O-Plan maintains an "agenda" of such flaws as part of the plan state. Other systems like UCPOP (Washington), OPIS/DITOPS (CMU) and DIPART (Pittsburg) also make the "I" part explicit in their plan representations (via an agenda or work list).

The set of nodes (N) included in the plan anchors the candidate set (non-primitive nodes may only be expanded through those operators available in the domain library which imposes a further constraint on the legitimate candidate set). The "OVA" (detailed constraints) and "I" (implied constraints) then further constrain the legitimate plans within the partial plan defined by the full <I-N-OVA> constraint set.

2 The Planning Process in O-Plan

This account is intended to show O-Plan as an instance of a "Refinement Planner" as described, for example, in the work of Khambhampati [4]. The text below deliberately uses the framework text provided by Khambhampati to show the relationship as clearly as possible.

2.1 Refinement Search in O-Plan

A planning problem is defined as a pair <T, D>, where T is a description of the task to be performed (it may also contain S, whose elements St are descriptions of the state of the world at a given point in time - for example one Si can be used to represent the initial state in which the plan is to be executed), and D is a description of the application domain. D is a pair <O, M> where O is a set of primitive operators or action descriptions possible in the domain being modelled, and M is the set of methods that may be used to expand non-primitive activities within the plan.

A plan P is said to solve the planning problem <T, D> if a ground operator (action) if every action in P contains only elements from O, that the reduction of any non-primitives operators or actions in the task T to the primitive actions from O was done only by using transformations from M, and it satisfies the specified task T.

Note that the "STRIPS" planning problem is normally defined just in terms of <S_i, T, O>, whereas a task reduction of hierarchical task network (HTN) planner is limited to generating solutions in which the hierarchical task reductions are within the set of methods (M) given.

Note that T could define actions that must be performed as well as (partial) goal states to be achieved, amongst other requirements.

O-Plan solves a problem by navigating a space of sets of potential solutions (which include combinations of actions). The potential solution sets are represented and manipulated in the form of "partial plans". Syntactically, a partial plan P is represented as a set of constraints. Semantically, a partial plan is a shorthand notation for the set of possible plans that are consistent with the given constraints. The latter set is called the candidate set of the partial plan.

O-Plan starts with an initial partial plan. Note in particular that this can be any partial plan in O-Plan. However, it is possible to start with a "null plan" whose candidate set corresponds to all possible combinations of domain actions. It is more usual to start with an initial plan that includes the initial state description (S) and the task requirement (T). It is possible to use O-Plan in an environment where multiple alternative pre-existing partial plans are refined further (for example, when using plan case libraries).

O-Plan then performs refinement planning, by successively refining the plan (by adding constraints, and thus splitting their candidate sets) until a solution is reached. Semantically, a refinement operator R (called a Plan Modification Operator in O-Plan) maps a partial plan P to a set of partial plans. This mapping is usually such that the candidate sets of the children plans are proper subsets of the candidate set of P. However, relaxation of constraints is possible within the O-Plan framework in some circumstances. Refinement planning involves repeatedly applying refinement operators to a partial plan until a solution is recognised within the candidate set of some resulting partial plan.

Except for the special case of a Plan Modification Operator that allows for relaxation of constraints, the refinement operators R in O-Plan are designed to be Complete and Systematic. A refinement operator R is said to be "complete" if every solution belonging to the candidate sets of a partial plan P belongs to the candidate set of at least one of the children plans. R is said to be "systematic" if the candidate sets of children plans are non-overlapping.

In the current implementation, this design aim is partially met. The search space is systematic with respect to teleologically distinct plans, but the action sequences involved in those plans can be the same. I.e. there can be different goal structure "approaches" (as in Interplan) to arriving at the same plan, but there will not be two plans produced with the same action sequence from the same approach.

2.2 Partial Plan Representation in O-Plan

A partial plan is a 5-tuple <I, N, O, V, A> where:

N is the set of nodes in the plan; Each member of N has an associated begin time point (referred to as "begin n") and an associated end time point (referred to as "end n"). Each node has a unique associated label or name. N contains two distinguished nodes n1 and n2. The special node n1 is always mapped to a dummy node with label "start", and similarly n2 is always mapped to "finish". The end time point of n1 is temporally before any other node in the partial plan. The end time point of n2 is temporally after any other node in the partial plan. The effects of "start" correspond to the initial state of the problem description (S).

O is a partial ordering relation over N.

V is a set of codesignation (binding) and non-codesignation (prohibited binding), and perhaps other, constraints on variables that appear elsewhere within the partial plan description (in I, N, V, and A).

A is a set of auxiliary constraints that restrict the allowable orderings and bindings among the nodes. Several such constraints may be represented in a partial plan:

- world state constraints
- resource constraints
- authority constraints
- other constraints (depending on the domain, e.g., spatial constraints).

It is possible to state these constraints with respect to zero, one (point constraints), two (range constraints) or more than two time points.

I represents a set of "issues" or "implied constraints" which further constrain the candidate set described by the partial plan. In O-Plan these are described as a set of nominated plan refinements (R - or Plan Modification Operators) that must be made and lead to a legitimate candidate set that is within the partial plan description.

2.3 Representing the Task to O-Plan

As mentioned above, the Initial State is attached as effects to the "start" node in a partial plan.

Other task requirements from the task description (T) are included in the intial partial plan provided to O-Plan. It is possible to represent "goal" state-related requirements by simply attaching world state constraints to the begin time point of the "finish" node. An initial state can be included as world state constraints on the end time point of the "start" dummy node. However, more comprehensive task description capabilities are utilised in O-Plan - such as the ability to state that actions must be included in the plan in certain prespecified orders, etc.

References

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