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QUALITATIVE MODELS FOR PLANNING: A GENTLE INTRODUCTION

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ABSTRACT

Qualitative Modeling is the study of how the physical world behaves. These physical models accept partial descriptions of the world and output the possible changes. Current systems assume that the model is static, and that physical entities do not effect change into the world. For instance a certain qualitative systems can diagnose faulty electrical circuits, but cannot design plans to rewire circuits to change their behavior. This paper describes an approach to planning in physical domains and a working implementation which integrates qualitative models with a temporal interval-based planner. The planner constructs plans involving physical quantities and their behavioral descriptions.

1. INTRODUCTION

This paper describes a system for the representation and solution of dynamic planning problems. The representation of physical entities in qualitative models provides an excellent forum for storing definitional and behavioral information about a particular domain [2,8,10]. This knowledge is easily coupled, in the model, with a temporal component permitting the representation of entity behavior and interaction over time. The temporal capability is accomplished with the introduction of a time interval into the qualitative knowledge model. Inference mechanisms that usually run with the detailed qualitative information are now time-qualified, adding another "dimension" to the knowledge model [6,10]. The prototype system developed to illustrate these concepts is described, and, finally, directions for future work are outlined.

2. QUALITATIVE MODELS

Qualitative models are aptly described by Williams[10] as a physical system with initial conditions whose analysis typically involves (1) a description of the temporal behavior of the system's state variables, in terms of a particular qualitative representation, and (2) an explanation how this behavior came about.

In more detail, a physical system consists of a set of state variables (e.g., force and acceleration) and a system of equations, parameterized by time, which describe the interactions between these variables (e.g., $f(t) = ma(t)$). A qualitative representation partitions the range of values for a particular quantity into a set of interesting regions (e.g., positive, negative, or zero). The particular representation selected depends on properties of the domain and the goals of the analysis.

The behavior of the system can be viewed in terms of a qualitative state diagram, where each state describes the qualitative value of every state variable in the system. The behavior of the system over time can be viewed as a particular path through this state diagram. Each state along this path represents an interval of time over which the system's state variables maintain their values. The duration of this interval is dictated by principles involving continuity and rates of change.[4,6,10]

The system changes state whenever any state variable changes its qualitative value. The values in the next state are then determined by (1) identifying those quantities which cannot change value (e.g., if q is positive in a particular state and its derivative is positive or zero then it will remain positive in the next state), and (2) propagating the effects of those quantities that are known to change. The qualitative reasoning system also keeps track of the reason for every deduction in (1) or (2), using the record, among other things, to generate explanations (e.g., "an increase in force causes the mass to accelerate").[5,6,10]

Components in a qualitative model may be expressed as an object containing five elements[3,9]: individual objects involved in the process, preconditions (outside of the object knowledge) on the behavior, quantity conditions (inequalities), relations asserted as object behavior, and influences the behavior has on quantities.

3. TEMPORAL INTERVALS

The planning system maintains a list of entity qualities or properties qualified by intervals over which they hold. The planner uses a time logic[1] to maintain the temporal relationships between intervals. Table 1 shows the possible values for different relations.

In operator and rules defined within the system, intervals are represented by symbols starting with '$', while variables are represented by symbols starting with '?'. The temporal relation between two intervals is expressed as a disjunction and written in a list (e.g., (:< :>) is used to mean "is before or after"). Different properties or facts about an object are paired with the same interval over which they hold. Thus, (ON A TABLE) $INTERVAL1 denotes a fact (ON A TABLE) which holds over the time interval $INTERVAL1.

Value	Description	Inverse	Description
:<	before	:>	after
:M	meets	:MI	met by
:O	overlaps	:OI	overlapped by
:S	starts	:SI	started by
:F	finishs	:FI	finished by
:D	during	:DI	encloses
:=	equals	:=	equals

TABLE 1: Interval Relations and Inverses[1].

An <u>operator</u> defines an action the object can perform to change its properties in the world. The planning system uses a model of action[1] with temporally qualified expressions describing operator preconditions and effects. For instance, Figure 1 defines an operator PICKUP which can be applied to an object if it is clear and resting on something. PICKUP's effects clear the object's old location. The constraints field is used to restrict the temporal relations among facts matching with the preconditions and effects.

```
OPERATOR: pickup
  PRECONDITIONS: (clear ?object) $clear-object
                 (on ?object $surface) $on
  EFFECTS: (pickup ?object ?surface) $pickup
           (clear ?surface) $clear-surface
  CONSTRAINTS: $clear-object (:M) $pickup
               $on (:O) $pickup
               $on (:M) $clear-surface
```

FIGURE 1: Definition of Operator PICKUP[3].

A <u>rule</u> models temporal laws of the domain. The planning system uses rules as backward chaining operators for solving goals, as well as forward chaining, temporally constrained inference rules. Thus, with the object behavior modeled as rules, the system can both plan their action and infer their results.

Rule definitions are similar to operator definitions, with antecedents behaving like operator preconditions, consequents behaving like operator effects, and consequence constraints behaving like operator constraints. The additional field, temporal conditions, places preconditions on the temporal relations among facts matching the antecedents. The time logic supports temporal intersections, allowing a rule to be inhibited until antecedents are known to intersect (meaning their relation is a subset of (:S :SI :F :FI :D :DI :O :OI :=)) and to assert consequents over their intersection. Figure 2 demonstrates these features. Given (ON A B) and (ON B C) whose intervals intersect, (OVER A C) is asserted during their intersection.[3,9]

```
RULE
  Antecedents: (ON ?x ?y) $on-xy
               (ON ?y ?z) $on-yz
  Temporal Conditions:
    Exists (INTERSECTION $on-xy $on-yz)
      called $intersection
  Consequents: (OVER ?x ?z) $intersection
  Consequent Constraints:
```

Figure 2: A Temporally Qualified Inference Rule[3].

4. APPLICATION

The constructs of the previous section are part of a simple temporal planning example to operate on selected objects. Plans can be generated to "pick-up" A, B, or C. This example is, however, very different from the typical "blocks world" environment in two respects, each object have been physically described and temporally qualified. The physical description portrayed the objects ability to placed over one another and even how many may be stack above each particular object. This aspect of the system has not been exploited in order to concentrate on temporal planning which give the intervals in which each object resides over another object. Figure 3 shows the script generated by the planner to meet a goal in this simple system.

```
Goal: PICK-UP A tl
Solution: Apply the rule to see if any objects are over A at tl.
  Goal: PICK-UP B
  Solution: Apply the rule to see if any objects are over B at tl.
    Goal PICK-UP C
    Solution: Apply the rule to see if any objects are over C at tl.
    Action: pick-up C
  Action: pick-up B
Action: pick-up A
```

FIGURE 3: Output for Goal to Pick Up Object A.

Qualitative models such as those described in this paper will be necessary for detailed planning operations onboard space station and for many other space applications. Planning systems using temporally-qualified structural and behavioral knowledge will be able to plan the independent actions of IVA or EVA robots, is needed to function in a dynamic, time-varying, environment[7]. Qualitative systems will also be able to generate complex plans for multiple experiment packages, using knowledge of core subsystem properties to keep operations within established constraints.

5. CONCLUSIONS AND FUTURE DIRECTIONS

Qualitative modeling represents the physical and temporal information required for dynamic planning applications. Characteristic and behavioral information describe an entity in term of properties which are used in different time qualified rules and operators to generate plans to achieve desired goals. A simple example of temporal reasoning about physical objects was presented, but examples of more sophisticated thermal and electrical systems of entities have been accomplished.

Work of this nature is helpful in developing and evaluating representations for qualitative modeling and planning, that is controlling the effects of time, space, and general properties of physical objects [6,7]. Current efforts in the design of the space systems are requiring the capture detailed knowledge of system design[7], so new space systems may incorporate advanced knowledge-based applications, such as planning systems driven by qualitative models. Accordingly, this research will continue to explore detailed representations within domain and world models, and investigate different planning strategies for reasoning and control.

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