

High Performance Techniques for Space Mission Scheduling *

Stephen F. Smith

The Robotics Institute, School of Computer Science
Carnegie Mellon University, Pittsburgh, PA 15213
Tel: (412) 268-8811; Fax: (412) 621-5477
E-Mail Address: sfs@cs.cmu.edu

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INTRODUCTION

In this paper, we summarize current research at Carnegie Mellon University aimed at development of high performance techniques and tools for space mission scheduling. Similar to prior research in opportunistic scheduling, our approach assumes the use of dynamic analysis of problem constraints as a basis for heuristic focusing of problem solving search. This methodology, however, is grounded in representational assumptions more akin to those adopted in recent temporal planning research, and in a problem solving framework which similarly emphasizes constraint posting in an explicitly maintained solution constraint network. These more general representational assumptions are necessitated by the predominance of state-dependent constraints in space mission planning domains, and the consequent need to integrate resource allocation and plan synthesis processes.

First, we review the space mission problems we have considered to date and indicate the results obtained in these application domains. Next, we summarize recent work in constraint-posting scheduling procedures, which offer the promise of better future solutions to this class of problems.

SPACE-BASED OBSERVATORY SCHEDULING

Our research has focused specifically on space-based observatory management applica-

tions, which, like most mission planning problems, require allocation of resources to competing goal activities over time in the presence of complex state-dependent constraints. Such problems are typically categorized as scheduling problems, where observing time must be allocated so as to optimize overall performance objectives (e.g., maximizing scientific return, balancing observing priorities). Yet classical scheduling frameworks, which emphasize formulation of scheduling problems as assignment problems, prove insufficient in this case. Since the executability of a given observation also depends on conditions of the predicted spacecraft state other than resource availability (e.g., the operating state of the required viewing instrument, spacecraft power levels and pointing direction, the visibility of the target, etc.), solution feasibility can only be guaranteed by dynamically generating and synchronizing the auxiliary activities necessary to bring about and preserve enabling state conditions. In short, effective solutions to these problems must integrate resource allocation and plan synthesis capabilities.

Given the above problem characteristics, our initial research focused on the development of a modeling and problem solving infra-structure that synthesized the respective strengths of planning and scheduling frameworks. This effort led to the development of HSTS [8,9], a problem solving architecture that promotes an integrated view of scheduling and planning as an opportunistic process of constraint posting in an explicitly maintained solution constraint network. The HSTS problem solving architecture was originally developed and applied in the context of the problem of constructing short-term observation schedules for the Hubble Space Telescope (HST), motivated by the limitations of the current solution. In the HST domain, several results with the HSTS problem solving architecture have been demonstrated. The leverage provided by HSTS's emphasis on decomposable domain descriptions was demonstrated through experiments with a se-

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quence of domain models that increasingly captured more and more of the telescope's operational constraints. The observation scheduler was shown to scale to the full problem, producing observation schedules complete with all necessary enabling activities such as instrument configuration, telescope repointing, data communication, etc. in a time frame acceptable for actual application [8]. Complementary results demonstrated the ability of "multi-perspective" scheduling techniques to produce better quality schedules, in terms of balancing conflicting mission objectives, than a variant of the short-term scheduling algorithm currently being used in HST mission operations [13].

More recently, HSTS has been used to develop of scheduler for application to a second orbiting telescope, the Small Wave Sub Millimeter Astronomy Satellite (SWAS), currently due to be launched in early 1995 [7]. The SWAS problem differs fairly significantly in character from the HST problem. Whereas scheduling in the HST domain is concerned with synchronization of well-specified programs of target observations, viewing goals in the SWAS domain are formulated as cumulative amounts of time to be spent on various targets. Thus, the SWAS scheduling task is to efficiently distribute and interleave viewing time among various targets. We have developed an initial, priority-based scheduling procedure, which operates with a domain model that ensures satisfaction of all dominant spacecraft operating constraints (e.g., slew time, target acquisition procedures, power constraints) and is designed to optimize an overall priority score defined by the SWAS mission team. The viability and potential of the scheduler was recently demonstrated using a provided set of reference targets and representative 1-week scheduling problems. In these experiments, the schedules generated show overall satellite utilization percentages of greater than 70% (over 20% higher than expectations provided a priori by the SWAS mission team), and problems are solved in 5-6 minutes on a SPARC IPX. During the coming months, plans call for integration of the scheduler into the SWAS mission planning software environment, and full-scale comparative testing against their current baseline approach.

SCHEDULING VIA CONSTRAINT POSTING

Methodologically, our research approach has been to combine incremental development of

solutions to specific application problems with more basic investigations into more broadly applicable and higher performance longer term solutions. In this section, we summarize our progress toward exploiting the constraint posting scheduling framework that is promoted by HSTS.

As indicated earlier, research in constraint-based scheduling has typically formulated the problem as one of finding a consistent assignment of start times for each goal activity. The HSTS framework, in contrast, advocates a problem formulation more akin to least-commitment planning frameworks: the problem is most naturally treated as one of posting sufficient additional precedence constraints between pairs of activities contending for the same resources to ensure feasibility with respect to time and capacity constraints. Solutions generated in this way typically represent a set of feasible schedules (i.e., the sets of activity start times consistent with posted sequencing constraints), as opposed to a single assignment of start times.

While frameworks such as HSTS do not prohibit the use of "fixed time" scheduling techniques, there are several potential advantages to a solution approach that retains solution flexibility as problem constraints permit. From the standpoint of solution use, the generation of sets of feasible schedules provides a measure of robustness against executional uncertainty, allowing determination of actual start times to be delayed and minimizing the need for solution revision. From the standpoint of solution development, a constraint posting formulation of the problem can provide a more convenient search space in which to operate. During schedule generation, alternatives are not unnecessarily pruned by the need to (over) commit to specific start times. When the need for schedule revision becomes apparent, modifications can often be made much more directly and efficiently through simple adjustment of posted constraints.

Given these potential advantages, recent research has focused on development and evaluation of constraint-posting scheduling techniques. One approach, generalizing directly from the concept of bottleneck analysis used in previous work in opportunistic scheduling but without the "fixed times" assumption, has led to development of a procedure called Conflict Partition Scheduling (CPS) [10]. Experimental analysis on benchmark constraint satisfaction scheduling problems showed CPS to outperform two state of the art "fixed-times" scheduling approaches - a

micro-opportunistic procedure [11] (based similarly on "contention-based" focus of attention) and a min-conflict iterative repair procedure [6].

Our more recent work has concentrated on the development of simpler, computationally cheaper alternatives to contention-based problem analysis when a constraint posting framework is assumed, leading to development of a procedure called Precedence Constraint Posting (PCP) [12]. PCP couples the use of previously developed dominance conditions for incremental pruning of the set of feasible sequencing alternatives [5] with a simple look-ahead analysis of the temporal flexibility associated with different sequencing decisions. At each step of the search, a measure of *residual temporal slack* is computed for each sequencing decision that remains to be made; the decision with the smallest residual slack is chosen as the most critical, and a precedence constraint is posted in the direction that retains the most flexibility. After posting the new constraint, dominance conditions are checked to identify other sequencing decisions that now have only a single feasible ordering; these unconditional decisions are also taken (i.e. the implied precedence constraints are also posted) before recomputing estimates of residual slack. The PCP procedure terminates when either all pairs of activities contending for the same resource have been sequenced, or an infeasible state has been reached. Experimental results with PCP on the same suite of constraint satisfaction scheduling problems have shown comparable problem solving performance to contention-based scheduling approaches with orders of magnitude reduction in computational time [12].

One of our principal current interests is applying the PCP procedure in more frequently encountered, optimization-based scheduling contexts (i.e., where the goal is not simply a feasible solution but a feasible solution that minimizes/maximizes some objective criterion). We are exploring two general approaches to adapting PCP for this purpose:

- *discrete relaxation search*, where PCP is embedded as a solution feasibility evaluator within a larger search through the space of possible constraint relaxations defined by the objective criteria, and
- *upper-bound improvement search*, where the PCP procedure itself is modified to directly incorporate the objective criteria (e.g., using estimates of "residual tardiness cost" as opposed to residual temporal slack),

and a dynamically adjusted upper-bound solution provides the basis for search space pruning.

The utility of each of these approaches depends on characteristics of the specific optimization criterion that is considered. For example, the common manufacturing problem of minimizing weighted tardiness is better formulated as an improvement search, since there is no structure to support an effective search through the possible due date relaxations of all jobs. In this problem context, we have performed some initial experimentation with a configuration of PCP that utilizes a dispatch heuristic to estimate the tardy cost associated with different sequencing decisions, and decisions are used to incrementally improve an upper bound solution. This extended procedure has been shown to produce schedules 10-30% better (depending on problem constrainedness) than the combined results of the best priority heuristics known for the weighted tardiness problem on a generated set of large (1000+ activities) scheduling problems (with average solution time of 1 minute).

One criterion that is straightforwardly formulated as discrete relaxation search, however, is minimizing makespan (or overall duration) of the schedule (or equivalently maximizing resource utilization). We have developed a procedure, referred to as MULTI-PCP, which first establishes lower and upper bounds on the overall completion time of the schedule (using a critical path method and a simple dispatch heuristic respectively), and then searches for the minimum feasible "common due date" by repeatedly applying PCP to various dates within these bounds. We have contrasted the performance of this procedure with that of the shifting bottleneck family of procedures (SBP) [1] (one of the best approximation algorithms currently known for minimizing makespan) on a set of previously studied benchmark problems. In these experiments, MULTI-PCP was shown to produce competitive solutions (more often than not closer to the optimum than the solutions obtained with the shifting bottleneck procedure) in equivalent or less computation time. Moreover, on tests of larger problems (involving 1000 activities), we have shown PCP to consistently produce better results than SBP with increasingly better computational efficiency [4].

All of the benchmark problems mentioned above make assumptions of fixed activity durations and simple precedence constraints between related activities (Indeed these are the problem as-

sumptions uniformly made in the classical scheduling literature.) In space mission scheduling domains, in contrast, goal activities may have imprecise (or adjustable) durations, and a much richer set of qualitative and quantitative temporal constraints may be imposed on goal activities. Recent experimental analysis with PCP on problems that incorporate such constraints has pointed up inadequacies in the use of simple temporal slack as a look-ahead bias; in such problem contexts, earliest (and latest) start (and end) time information provides a much less accurate estimate of temporal flexibility. To overcome this limitation, we have recently generalized our look-ahead model of temporal flexibility to instead rely on "shortest path" information [3] This extends the applicability of PCP to the full range of temporal constraints expressible in HSTS. Our short term plans are to further develop and apply this approach to the core SWAS scheduling problem of maximizing utilization under cumulative activity duration constraints.

Finally, we mention our recent application of constraint-posting scheduling techniques in a domain of some relevance in other space mission planning arenas: scheduling experiments in an automated robotic chemistry workstation (resident at CMU) to maximize parallel experimentation. This problem is dominated by the presence of finite temporal separation constraints between successive steps of individual experimental plans (e.g., a chemical reaction must be sampled by the robot 2 hours after the last sample taken). By developing a constraint-posting variant of the existing "fixed-times" scheduling procedure and introducing the capability to support flexibility in constraint specification, the utilization of the workstation was almost doubled [2]. A version of this scheduler has been operational since September, 1993.

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