Planning the Operations of the Scientific Instruments of a Spacecraft on a Planetary Mission

An Example of Scheduling Optional Tasks in an Over-Constrained System of Dependent Unary Resources

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Abstract

The problem of planning the operations of the scientific instruments of a spacecraft on a planetary mission is characterised by the presence of a considerable big number of optional activities, which are competing for few limited shared and hence over-subscribed resources. Diverse dependencies among the activities give rise to a vast number of constraints and make it a valid representative of the large to medium-size real-world practical problems, which include both aspects of planning and scheduling.

Introduction

The European Space Agency, ESA, has launched a number of planetary missions such as Mars Express, SMART-1, Rosetta and Venus Express in the recent years. The prime objective of these missions is to carry out scientific measurements, which shall lead to a better understanding of their target planet or comet. The spacecraft of such a planetary mission can generally be divided into two main groups of sub-systems: the satellite bus and the scientific instruments, the so called payload.
The planning and coordination of the operations of the scientific payload instruments is the main responsibility of the Science Operation Centre, SOC, of such a planetary mission. Each of these operations requires several spacecraft resources and can only perform under certain, predefined environmental conditions. Examples of such conditions are the satellite distance to the target, the local solar angle on the target, etc. These environmental conditions must therefore be simulated in advance and be analysed carefully for the entire planning period. The operations of all instruments must be prepared, coordinated and planned in detail, taking several engineering and spacecraft related constraints and limitations into consideration, including the following:

- The limited satellite resources such as the available electrical power and the on-board memory capacity.
- The satellite can have a single orientation towards certain coordinates in the space at any given time. This makes many observations incompatible for running in parallel.
- The operations of the scientific payloads should not interfere with spacecraft maintenance, attitude control, and other platform activities.
- The thermal and illumination constraints of the spacecraft and individual payload must be considered.
- Some scientific objectives of the mission can only be achieved in the context of a campaign in which several instruments perform different interrelated operations.

All these constraints make the planning and scheduling process a complex, iterative and time consuming task.
One of the most important characteristics of the problem is however the aspect of the optionality of almost all activities. There are namely always much more science opportunity windows available than can be planned. The details of this planning problem and a possible approach to its solution are presented in this paper.

The Problem

ESA planetary mission are organized as so called PI-driven missions. In these missions each payload instrument is designed, built, and operated by a team of scientists, led by a Principal Investigator, in short PI, who carries the final responsibility for the operations of that instrument and provides the science operations centre with scientific inputs and the results of the already performed measurements of his/her instrument. The Science Operation Centre interacts with all PIs in order to coordinate and plan the activities of all payloads and to insure the achievement of the overall scientific objectives of the mission.
In our presented approach, the science operations planning process begins with the submission of so called *Observation Requests* by the PI's. An observation request contains all relevant scientific and operational information,

which are required for planning an observation of a single instrument. This information includes:

- Environmental conditions, under which the observation can perform, such as the distance to a target, or illumination and visibility conditions
- A group of target objects, such as landmarks on a planet, stars, etc., for which the observation request has been made
- The orientation of the spacecraft during the observation of the target
- The detailed but not time-tagged operation flow, which has to be performed during the observation
- The scientific justification for the request.

It is essential for the presented concept to understand that an observation request does not include any information about the actual date, the orbit number and the time of execution of the required observation. Observation Requests are made by the payload teams purely based on the scientific and environmental criteria. They describe the measurements, which must be performed by each instrument, in order to achieve or contribute to some scientific objectives of the mission and the condition, under which they shall perform.
After the collection of all the different observation requests, it is the responsibility of the Science Operations Centre to perform a detailed environmental simulation and analysis for a complete period and to identify a set of time slots in which the different request can be performed. These time slots are called *Science Opportunity Windows*. They specify periods of time during which all specified conditions of the corresponding requests are valid.

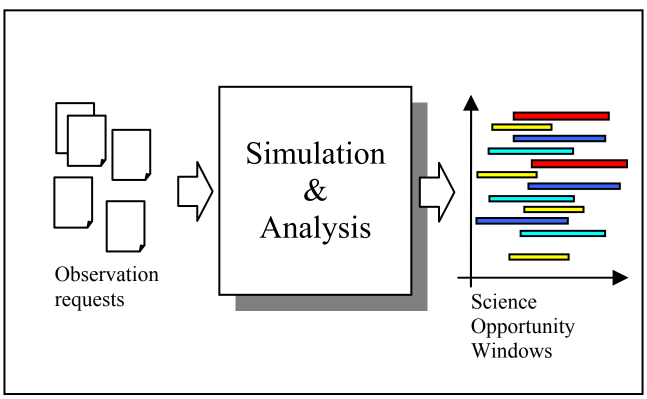

Figure 1: Science Opportunity Analysing

The actual scheduling process begins after all science opportunity windows of a planning cycle are identified. It involves very often many overlapping windows, which compete for the same limited and shared resources, hence the optional tasks. The scheduling process can therefore be seen as the distribution of these shared resources among the payload instruments over the time, avoiding any conflicts. It involves selecting a subset of observations among overlapping and competitive science opportunity windows (the planning aspect) and the subsequent scheduling of the selected observations with respect to the available satellite resources. The automation of this planning and scheduling process and the creation of a conflict free operation plan for the payload instruments with an optimised overall scientific output of the mission is the main objective of the presented approach.

Formal Description

This section shall provide a more formal definition of the above presented problem. In particular it shall describe the following aspects: definition of optional tasks, resources and constraints of the problem, and possible objective functions to measure the quality of the solutions.

(Optional) Tasks

Each Science Opportunity Window can be viewed as an Optional Task **T** defined by its:

- **start(T)**: start time of the observation;
- **end(T)**: end time of the observation;
- **d(T)**: variable duration;
- **point(T)**: required satellite orientation (pointing type) during the observation;
- **power(T)**: power consumption;
- **data(T)**: total amount of generated data during the observation.
- **priority(T)**: the priority of the task

The optionality of the tasks can be modelled in various ways, e.g. allowing zero duration values, adding a new Boolean indicator to each task, which shall determine if the task is omitted, not specifying the start and end time of the task, etc.

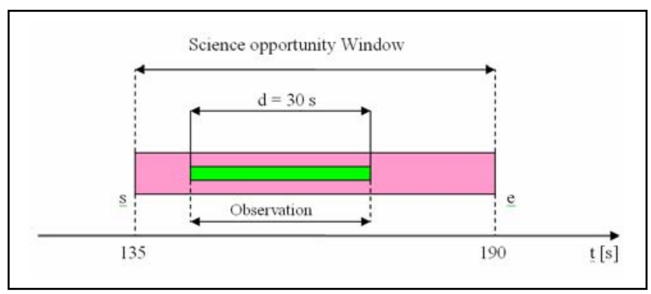

Figure 2: Modelling of a SOW as an optional Task

Using this representation the above described problem can be turned into a pure scheduling problem, which aims to label the start and end times of the (optional) tasks and to find a valid allocation of them on the available resources, while taking all defined constraints into consideration. The constraints of such a scheduling problem are described below.

Resources and Constraints

The available **electrical power** and the **onboard data storage** are two major limited and shared resources between all tasks. Both are consumable but regenerative resources with a fixed limited and constant capacity. In more advanced modelling techniques the capacity of the power resource is not constant and shall be modelled as a variable. The power generation of the satellite may be dependent on its attitude towards the sun and on other factors of the solar arrays.
Considering these two resources needs to add dummy tasks which would model respectively the recharge and the downlink process. In other words, these tasks will allow to refill the power resource and to free the consumed memory capacities.

A scientific instrument or **payload** can only perform a single observation at any given time. Each payload represents therefore a new unary resource (like a machine in the Job-Shop-Scheduling Problem) on which its own observations shall be scheduled.

The orientation of the spacecraft (**pointing**) is an additional but more complex resource, which can be modelled in various ways, including a set of unary resources or a capacity resource (the details of the implementation techniques are not in the scope of this paper and can be found in [5]).

The **thermal constraints** of the spacecraft are the next challenging resource constraint type. Since they can not be specified in a static way and must be considered dynamically based on the selected attitude of the spacecraft during an observation and the resulting illumination of certain areas of the spacecraft.
In the first abstraction this can be modelled by static pre-defined rules, which restrict the duration of certain pointing types and define a matrix of allowed and forbidden successive pointing types.
Additional temporal constraints are required for modelling any required order in the execution of the tasks or for specification of the so called slew times, the time required by the spacecraft to obtain a certain orientation starting from a different given attitude.
A more realistic and hence advanced modelling shall take other platform aspects such as reaction wheel saturations and star tracker blinding aspects into consideration, while modelling the slew time constraints.

Objective functions

The simplest static objective function can be formulated as a weighted sum of the priorities/scores of all tasks, which constitute a final schedule/plan. More sophisticated optimisation functions may take also the history of already performed observations (previous plans/schedules) as well as the future plans into consideration. These elaborated techniques add the factor of how many times an optional activity may be planed in future if it is omitted in the current plan. They evaluate and label the priority parameter of each optional task dynamically based on a number of other domain specific factors such as

- duration of the observation: the priority of an observation may be specified as a function of its variable duration
- Campaign and cross instrument observations: The priorities of a set of observations of different instruments may change dynamically, based on the number of the observations which are scheduled to perform in parallel or in a given time window. This is typically the case in so called observation campaigns, where more than one instrument shall perform their measurements on the same object, in order to achieve a certain scientific objective

The more advanced an objective function become the more the scheduling problem moves towards the goal based planning. In the context of the presented problem the most advanced objective function may allow a science objective (goal) based scheduling.

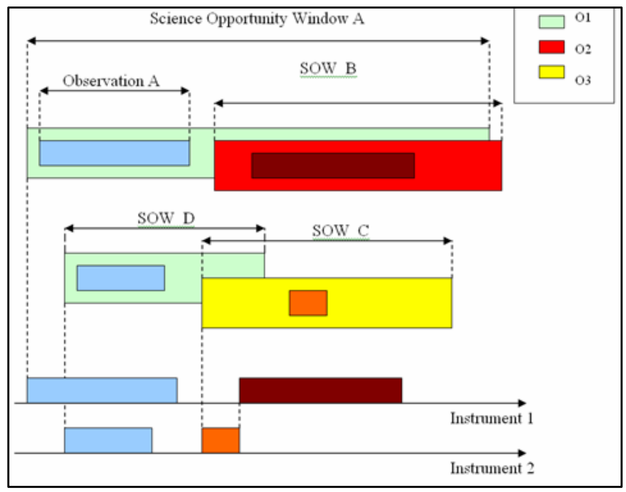

Figure 3: Example of 4 tasks / 3 different pointing types

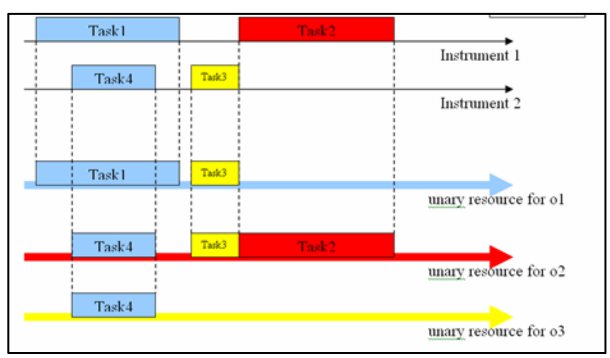

Figure 4: A possible allocation of the tasks to the pointing

Issues on modelling the problem

In this section we want to discuss a few issues we faced in trying to model the problem as a Constraint Optimization Problem. We think these comments can be useful to select an appropriate language for representing scheduling problems. In fact the usage of a particular language to represent the problem can bias the efficiency of a scheduling approach.
Two are the points we want to highlight here: the pointing constraint of the satellite and the optionality of the tasks.

Two different modelling techniques have been implemented for the pointing resource:

1. using a set of cumulative and unary resources, i.e. one cumulative resource for each pointing type;
2. Using a nxn matrix of single disjunctive constraints, where n is the number of payloads.

Two alternative modelling techniques have been implemented to capture the aspect of the optionality of the tasks:

1. Adding the zero value to the domain of the duration variables. A Boolean weight variable is added to the model, which is linked to the zero value of the duration variables via a so called Kronecker constraint. The weight variable is in turn involved with the score/priority variable in a weighted sum constraint, so that the score of the tasks with zero duration is automatically set to zero.
2. The second approach allows only none-zero positive values for the duration variables of all tasks. Another Boolean variable is used in this modelling which indicates if the optional task is omitted or included in the final schedule.

The second approach allows to represent explicitly whether an activity is present or not in the final plan. Notwithstanding it requires a major extension and adaptation of many resource constraints as well as the search and labelling algorithms.

A further aspect

The introduced specification of the described problem and its reference implementation represent like in case of many other real-world practical problems only a simple abstraction of the complex real problem boundaries and constraints. Most of the mentioned resources are non-discrete, but continues and real valued resources. Their availability and capacity is mostly dependent on a number of other factors and must be calculated dynamically.
Good examples for this kind of resources and constraints are the electrical power resource and the slew time constraints. The power is dependent on the current altitude of the spacecraft and the position of the Sun, while the slew time depends among other factors on the current rates and the saturation limits of the reaction wheels as well as forbidden areas of the sky, which must be considered in order to avoid star tracker blinding effects or to protect the CCD of some sensitive imaging instruments.
Even the data generation and the duration of subsequent observations of a payload may depend on their predecedor observation. An imager instrument may for instance require a calibration after or before certain activities, which affects its resource usage.

Related Work

The problem described in this paper is an oversubscribed scheduling problem that is a problem in which there are more requests that can be accommodated with the available resources. Many real-life applications consist in scheduling resources that are oversubscribed. In this section we present two examples of such problems in the area of space applications. Both of them present some similarities with the problem so far discussed.
A first example is the Satellite Scheduling problem, where hundreds of requests compete for resources such as antennas at ground stations, instruments, recording devices, and transmitters on the satellites. Typically, more observations need to be scheduled than can be accommodated by the satellites and the ground stations. Such observations as well as the communication between the satellites and the ground stations depend on the satellite visibility. General descriptions of satellite scheduling problems are provided in [2,3].
A second example is the Telescope Scheduling problem. Some aspects of the problem make it very similar to satellite scheduling. For example, in both telescope and satellite scheduling, windows of visibility are defined; also, setup times are associated with the viewing instruments (telescope) and antennas (satellite scheduling) and the weather impacts on the visibility conditions. In most cases, there are more requests than can be scheduled. A simplified version of the Hubble Space Telescope problem is described in [10]. It is assumed that only one instrument can be active at any time; the setup time needed to reconfigure the instrument to be used is assumed to depend only on the previously used instrument. Two conflicting objectives are identified: maximizing the resource utilization (in this case telescope utilization) and rejecting as few candidate observations as possible.

Conclusion

Planning the operations of the scientific instruments of a spacecraft on a planetary mission represents a challenging example of real-world practical problems, which include both aspects of planning and scheduling.
The modelling and specification of this problem does however not constitute the major difficulty and can fully be covered through the well known techniques of the conventional scheduling.

It is much more the solving of the specified problem, which requires the implementation of more elaborate searching techniques and significant adaptation of the existing standard search and labelling algorithms.
To address the more advanced aspects of the presented problem, non-traditional scheduling methodologies such as dynamic constraint satisfaction and interaction of the simulation and scheduling frameworks are required.

References

1. P. Baptiste, C. Le Pape, and W. Nuijten, *“Constraint-Based Scheduling”*, Springer, 2001.
2. E. Bensana, M. Lemaître, and G. Verfaillie, *“Earth Observation Satellite Management”*, In Constraints, 4(3), pp. 293-299, 1999.
3. J. Frank, A. Jonsson, R. Morris, and D.E. Smith, *“Planning and scheduling for fleets of Earth observing satellites”*, in International Symposium on Artificial Intelligence, Robotics, Automation and Space, iSAIRAS’01, 2001.
4. M. Hoche, H. Müller, H. Schlenker, and A. Wolf, *“A Pure Java Constraint Programming Engine”*, In Proceedings of the 2nd International Workshop on Multi-paradigm Constraint Programming Languages (MultiCPL’03) at the 9th International Conference on Principles and Practice of Constraint Programming, 2003.
5. A. Jonsson, P. Morris, N. Muscettola, and K. Rajan, *“Planning in Interplanetary Space: Theory and Practice”*, in Proceedings of 5th Int. Symposium on AI, Robotics and Automation in Space, ESTEC, Noordwijk, Netherlands, 1999.
6. M. Sarkarati, *“Scheduling Optional Tasks in an Over-Constrained System of Dependent Unary Resources, Using a COP approach”*, TU-Berlin, 2007.
7. M. Sarkarati, D. Frew, and M. Almeida, *“Design and Implementation of a New Generic Planning Software System for the Science Operations of ESA Planetary Missions”*, IAC conference 2006.
8. M Sarkarati, *“Science Operation Planning Concept for Smart-1”*, ESA, S1-RSSD-TN-0009, 2006.
9. D.E. Smith, J. Frank, and A.K. Jonsson, *“Bridging the Gap Between Planning and Scheduling”*, Knowledge Engineering Review 15(1), 2000.
10. S.F. Smith and D.K. Pathak. *“Balancing antagonistic time and resource utilization constraints in over-subscribed scheduling problems”*. In The Eighth IEEE Conference on Applications of Artificial Intelligence, Monterey, CA, 1992.
11. P. Vilím, R. Barták, and O. Čepek, *“Extension of O(n log n) Filtering Algorithms for the Unary Resource Constraint to Optional Activities”*, Constraints, 10(4), pp. 403-425, October 2005.