Mission Planning Systems for Earth Observation Missions

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Abstract

This paper describes two different approaches to Mission Planning for earth observation missions: the approach followed in European Space Agency's ATOS-4 mission planning system prototype, and the approach followed for the operational Flight Operations Segment Mission Planning System of the Envisat earth observation mission. Both systems are introduced in their respective context, together with the underlying goals and constraints that have driven their development. Finally the re-usability of the ATOS-4 approach in the scope of an operational mission is discussed.

Introduction

The Advanced Technology Operations System (ATOS) of the European Space Agency is a programme of studies into the integration of advanced applications (including knowledge based systems (KBS)) with ground systems for the support of spacecraft mission operations. The automated functions of present-day Mission Control Systems (MCS) do not yet support all aspects of mission operations. Continuous advances in the engineering technology of the space segment make possible, and bring demands for, ever-increasing complexity of mission goals and products, and hence of the mission operations tasks. At the same time there is continual pressure to reduce the costs of mission operations. The ATOS studies were conceived to tackle the problems of integrating advanced applications into a MCS while promoting re-use of existing applications, and to demonstrate the benefits to mission operations of such an advanced MCS.

The Mission Planning problem has been addressed in the scope of several of the ATOS studies, with the ambition of leading to a better understanding of the use that could be made of advanced applications in operational systems.

The sections below describe the approach developed in the ATOS-4 project. They are followed by the description of the operational Mission Planning System developed as part of the Flight Operations Segment of the Envisat-1 mission, which illustrates the differences between prototype and operational systems.

ATOS-4 Mission Planning System

ATOS-4 Project

Automated mission planning systems are essential components of an advanced MCS. The ATOS programme addresses the problem of automating off-line mission planning and on-line mission re-planning in several distinct studies. ATOS-4 is one of them, which mainly addresses the problem of developing a generic infrastructure for automated mission planning systems integrated with the other components of an advanced MCS, and demonstrates it in the context of an earth observation mission, ERS-2.

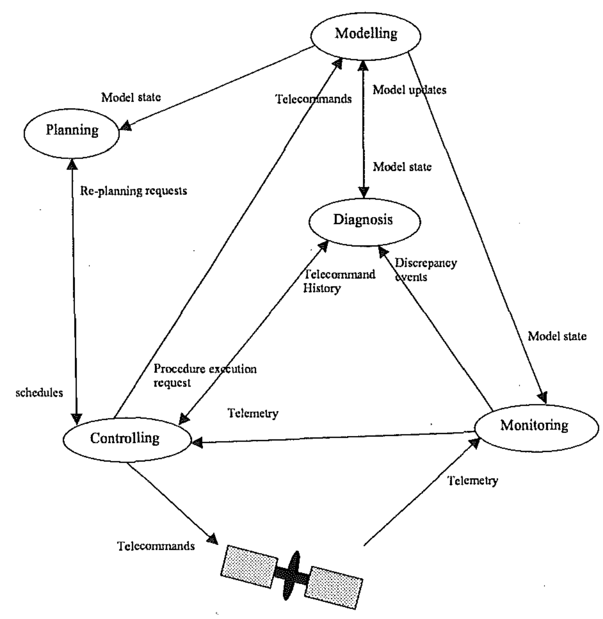

Figure 1: ATOS-4 MCS

The ATOS-4 project has developed a prototype of an Advanced Technology MCS which integrates and automates the application functions of operations schedule planning and generation, schedule execution and control, spacecraft health monitoring, real-time and predictive model-based monitoring, anomaly diagnosis and recovery. The project's goal was to produce a logical model for an integrated model-based MCS, and to provide the basic components of standard libraries that can be used for the development of such a system.

The ATOS-4 mission planning facility provides two main modules fully integrated with the other components of the MCS: an off-line planning system and an on-line re-planning system. To address the need for reusability of these components, both of them are delivered as part of a C++ library.

Planning Interfaces

ATOS-4 is a prototype Mission Control System, which is composed of five main components, as illustrated on the diagram of Figure 1, which communicate with each other through a communication infrastructure.

The Planning component, itself composed of the planner and re-planner applications, and of a collection of data editors, interacts in operations with only two other components, the Modelling component and the Controlling component. These interactions are further detailed below.

Planning and Modelling

The key feature of ATOS-4 is the use of an Object-Oriented model of the mission to support the operations. The mission model includes structural and behavioural information about the mission, which are needed to support predictive monitoring, i.e. simulation of the future state of the mission, diagnosis, and mission planning. The Modelling application provides services either to query the static information included in the mission model, or to trigger a simulation of specific states of the model, which can in turn be queried.

The Mission Planning System holds its own representation of the information included in the mission model, which it populates by querying the model for the data needed. The planner accesses the mission model to configure its activity database from static information held in the model about the mode transitions of the instruments. It uses model simulation to derive resource profiles by extraction of parameter values stored in the model, and get the starting state of the mission from which planning of activities must start.

Planning and Controlling

The end result of the planning process is a set of schedules, which can be executed by a dedicated Controlling application. Executable schedules consist of a partial ordering of procedure execution requests, with attached start time window, precondition, and expected result. Several types of relationship between execution requests are handled by the Controlling application, namely precedence relationship and causal dependencies. In the planning process, schedules are always generated as increments to schedules that have been prepared in a previous planning session, and chosen for execution. The Controlling application monitors the execution of the selected schedules, checking the validity of the precondition of the execution request before releasing them, and checking the expected result of the requests after execution. If the Controlling application is not able to execute the schedule as expected, i.e. if the expected precondition or effects of a procedure execution request is not valid, or if the release of a procedure execution request is delayed outside its start time window, a re-planning session is started.

In a re-planning session, the Planning component receives from the Controlling component a description of the state of all activities in the schedule. It uses it to create an updated partial schedule from the initial schedule in execution, from which the re-planning session is started.

ATOS-4 Planner

The central problem of mission planning is the generation of sequences of procedures which implement user and operational requests. With respect to this problem, the goal of the ATOS-4 Project has been to experiment with the use of partial-order planning and constraint-based reasoning methods to derive a generic model for a mission planner. The sections below describe the elements of the planning logical model, and the planning process.

Services. The first step in the planning is to generate primary activities from user or operational requests selected from the pool of requests available for planning, on the basis of their preferred execution time window, and their priority. Services are defined in the planning database, one for each type of request accepted by the planner. A service defines a static mapping of a request, with preferred timings and arguments, to a set of activities on the plan.

Activities. Two types of activities are handled in ATOS-4: transitions between instrument modes, or maintaining an instrument in a given mode.

Activities are characterised by

- A conjunction of preconditions on the model and plan state.
- Effects on the model and on the plan state.
- Constraints on existing resources (use as well as provision).
- An actual procedure, executable by the controlling application.

The planning makes use of the required enabling conditions of the primary activities to generate secondary activities whose effects match those conditions. The resource constraints are propagated during planning, and solved when all required activities have been generated on the plan.

Resources. The planner handles several types of resources:

- State resources (e.g. in eclipse).
- Consumable resources (fuel).
- Reusable resources (link).

Initial profiles for these resources are sampled at intervals depending on orbital event timings. The initial resource profiles are generated from the mission model by simulation and query. These profiles are then affected by the activities generated in the course of planning.

Planning algorithm. The planning algorithm is divided in two consecutive steps.

- The planning itself, i.e. generation of the secondary activities required to enable the primary activities and completion of the instrument timelines. This is performed through partial-order planning, based on the UC-POP algorithm. Each time a new activity is put on the plan, all the constraints attached to it (resource, temporal, etc.) are posted and propagated.
- An additional scheduling step, using constraint-based reasoning to solve the constraints derived during the planning.

Planning steps. The steps followed by the ATOS-4 Planner can be summarised as follows:

1. Get a model instance representing the state of the mission at the start of the plan, produced by model simulation.

2. Generate the resource profiles by simulation and query of the model.

3. Read the user requests and generate the corresponding primary activities in the order of priority of the requests, using the service mechanism. If a primary activity implementation results in resource conflicts that cannot be solved, the primary activity is descoped.

4. Generate the secondary activities required to enable the primary activities and complete the instrument timeline. If the secondary activities cannot be created for a given primary activity, the primary activity and all derived secondary activities are descoped.

5. Map the activities generated to procedure execution requests.

ATOS-4 Re-Planner

The ATOS-4 re-planner has internally the same structure as the ATOS-4 planner. The difference between the applications lies in the on-line nature of the re-planner, and on a specific interface for receiving re-planning requests.

Re-planning can be triggered in several situations:

- Failure of a procedure execution, e.g. because the procedure could not be started in its execution time window.
- Introduction of a new request for procedure execution to be implemented with high priority, typically a request generated by the Diagnosis system.
- Report on direct execution of an immediate recovery procedure triggered by the Diagnosis system, by-passing the planner.

A re-planning request consists of a description of the state of the schedule being executed, including actual execution time for the executed procedures, as well as the identification of the procedure executions that have failed, new procedures to be inserted, and procedures whose executions have been triggered by another source.

The re-planner can then deduce the whole set of procedures that could not be executed from the nature of the dependencies between the activities on the plan, and produce an updated plan and the corresponding schedule, which is directly transmitted to the controlling application.

Implementation

The ATOS-4 system has been implemented on UNIX SUN workstations as an extension of ESA's Spacecraft Control and Operation System II (SCOSII), with C++ as main implementation language.

The Kappa development environment from Intellicorp has been used for many of the knowledge-based elements of the ATOS-4 MCS, in particular for the mission model.

ILOG Solver and ILOG Scheduler have been used in the constraint-based reasoning module of the Planning component.

Lessons Learned

The main objectives of the ATOS-4 study were to understand better the problems of integrating a large and complex automated system with advanced functionality for mission control, and to evaluate the use of such a system for various types of mission.

The ATOS-4 system has been configured for evaluation purpose to cover part of the needs of ESA's earth observation mission ERS-2.

Configuration and trials of the mission planning system have revealed the following problems:

Mission Modelling. The use of a multi-purpose Mission Model results in consistency and efficiency problems.

The ATOS-4 Mission Model covers the needs of three different applications: simulation, planning, and diagnosis. Both planning and diagnosis use abstractions of the simulation model. For instance, the planner derives the initial resource profiles for a plan from mission simulation. An active mission model is executed, and the planner extract samples of model variables at intervals from orbital events. These samples are then used to build the resource profiles. This allows relatively complex physical properties of the model, such as the battery charge, to be used to provide to the planner a profile for a resource. This approach stresses the need for controlling the consistency of the simulation model and its abstractions, which is essential for the development and maintenance of the model. In the current implementation, the use of mission simulation for planning also appears to be computationally too costly.

Procedure Modelling. The modelling of a complex procedure by an activity is difficult. The procedures planned automatically should be restricted to command sequences.

The notion of procedure in ATOS is directly derived from the notion of automated operational procedure. As such, it is a program in an operational language that can include not only sequences of activities, but more complex constructs such as loops, etc. There are two types of procedures in ATOS: the time-tagged procedures, which are restricted to sequences of time-tagged activities to be executed on-board, and the standard procedures, which cover on-board and on-ground activities, and have to be executed through direct commanding (i.e. the satellite has to be visible from a commanding groundstation). Most of the procedures planned by the planner are time-tagged procedures (in many cases they include only one activity, corresponding to an instrument operation). One exception is the case of the diagnosis procedures, which perform checks on the systems and collect data for analysis. The ATOS-4 Mission Model includes information about the constraints related to the execution of atomic activities. When these atomic activities are combined into more complex structures that are not sequences, it becomes more difficult to model even simple properties that are needed by the planner, for instance minimum and maximum duration as a function of the arguments of the procedure.

Note that this notion of procedure does not exist in operational systems such as ERS or Envisat. For instance the Envisat FOS MPS plans atomic activities and sequences only.

Control of the Planning Algorithm. The performance of the planning algorithm does not allow handling of large numbers of dependencies between the activities and the states of the system.

This problem is partly due to the implementation itself. Nevertheless, it is likely that using the same approach in a realistic case will result in major performance problems. The key issue here is to find a way to control the planning mechanism so that the user gets an answer in a reasonable amount of time. The ATOS-4 planner incrementally updates the plan by considering in turn requests according to their priority. Requests that cannot be met are descoped from the plan. The re-planner ensures the availability of an updated plan within the interval between two commanding pass by interrupting the planning at a configurable interval between the pass and providing a solution. This approach is not elaborate enough for handling real cases.

Planning Constraints. The representation of the mission planning constraints through preconditions and effects would require the extension of the expressiveness of the language used to represent them, and therefore an extension to the planning algorithm which would make it ineffective, at least in its current implementation.

In ATOS-4, the activity preconditions and actions are limited to conjunctions of predicative forms. They express conditions that must hold before and when the activity is executed, and effects during and after the execution. They do not cover delays between related events. They do not cover either the case when the condition that enables an activity, or at least makes it sensible, must take place in the future of the activity. These cases would have to be handled, as well as disjunctive preconditions and conditional effects as they appear in UCPOP.

From ATOS-4 to Envisat FOS MPS

The limitations of the ATOS-4 planner, and the specific interfaces it requires for integration to the rest of the ground segment component, reduce considerably its direct applicability for planning a full-size earth observation mission. The Envisat Flight Operations Segment Mission Planning System, described here below, is an example of a planner for such a mission.

Envisat-1 Mission

ESA's new earth observation mission Envisat-1 will be launched in 2001. It has more options available than its ERS predecessors, including 9 instruments and a more complex Data Management System, and these factors have an important impact on the complexity of the Mission Planning.

FOS MPS and Distributed Planning

The FOS MPS is the final link of a chain of planning systems that contribute towards the overall planning of the Envisat payload and ground segment. Each of these planning systems is responsible for the performance of certain planning actions, the results achieved being passed down the line for further consideration and manipulation. These planning functions recognize three distinct planning levels – the amalgamation of these three sub-missions (listed below) forming the overall mission.

- The Global Mission - the ongoing operations that represent the long term mission strategy.
- The Background Regional Mission - more specialised than the Global Mission in that it defines a utilization strategy for regional instrument modes.
- The Regional Mission - specific requests that will tend to have a higher priority compared with the other types of Mission. These activities are not continuous in nature, and cannot be determined in conjunction with predefined events.

The FOS MPS must merge the content of the Regional Mission and Background Regional Mission information, provided by the Mission Configuration Facility planning component, with the Global Mission Plan, generated by the

FOS MPS in order to produce the consolidated Mission Plan. Further checking will be performed upon this final plan, to ensure that the planned operations are conflict free, and that they do not exceed the imposed satellite constraints.

Once it has been confirmed that the plan is acceptable, the command schedules needed to drive the spacecraft itself, the Station Computer (STC), and the Reference Measurement System (RMS) are generated.

Design Constraints

The Envisat FOS Mission Planning System consists of a suite of applications that cover the overall functionality described here above. The central application of this suite is the Plan Engine, responsible for the merging of events generated from the three sub-missions, and for detecting and solving conflicts between elements of the sub-missions and resources available.

The following key factors have influenced the design approach.

Specification of the planning requirements. The planning requirements are usually specified as rules which identify a situation and an action to be taken when the situation occurs on the plan.

Dynamic of the planning requirements. Planning requirements may be modified in the course of the mission, to adapt to the evolution of the mission, or to optimize its usage.

Use of external routines. The planning of several instruments is actually performed by external routines provided as C libraries by the customer, which have to be integrated in the Plan Engine software.

User Interaction. The requirements on the interaction between the user and the Plan Engine impose to consider the planning as a set of intermediate steps, which can be selected individually by the user.

Rule-Based Approach

Starting from a planning logical model similar to the ATOS-4 one, the elements described above have led to the following design for the Envisat FOS MPS:

- replacing in the planning model the planning algorithm for generation of secondary activities by a rule-based system.
- dropping provisionally the constraint-based reasoning element of the system, which is not justified by the nature of the problem.

The proposed use of rules to support the planning algorithm of the Envisat FOS MPS aims at keeping the planner more configurable with respect to changes to the mission specification rules and constraints. It also allows giving more control to the user on the planning process via control of the sets of rules to be executed on the plan. Its drawback is the hard-coding of the dependencies between activities in rules, which prevents the system from finding solutions that could be produced by a conventional non-linear planning algorithm.

The rule-based component of the Envisat FOS MPS is delivered as a C++ library of standard conditions and actions, which can be used to create rules. The rule condition and action evaluations are directly written in C++ in the code of the classes.

Although the idea of a generic rule-based planning system seems attractive and elegant, implementing a generic rule language to implement the planning steps would be rather risky. The dangers are

1. To produce a rule language whose expressiveness would not cover all the needs of the Envisat FOS MPS.

2. To produce a complex language which would make difficult the maintenance of the system.

3. That the design of a generic language would require a significant effort, especially in the generalization of concepts, which is not required by the final goal of the project, i.e. the design and implementation of the Envisat FOS MPS.

The alternative is to implement a simpler rule mechanism based on a C++ library including a generic rule class and a set of condition and action classes on the plan and on the Mission Planning Database. Specific conditions or actions that cannot be expressed using the basic set available can be created by specialization of the condition or action classes, leaving to the programmer the full expressiveness of C++ to code them.

In doing so, we avoid the development of a dedicated operational language for planning rules, while ensuring a minimum query/action structure in the way planning steps are implemented.

Implementation

The Envisat FOS Mission Planning System is being implemented on SUN ULTRA workstations, with C++ as implementation language. Release 2.0 of the Envisat FOS MPS has been delivered to ESA in October 1999, and has been accepted by the Agency.

It is expected that the system will be extended in the future to accommodate other missions of the same nature as Envisat, and to integrate alternative planning algorithms.

Conclusion

This paper aimed at giving an overview of two different approaches to mission planning systems, both driven by the ideal of software re-use and genericity. In each case, the ultimate goal is of course different. The ATOS-4 planner aims at demonstrating the feasibility of automating on-ground operations by integrating advanced applications to a prototype Mission Control System. The Envisat FOS Mission Planning System is an operational system, whose development is also driven by requirements for safety, stability and maintainability, as well as by operational considerations.

There are several factors which hinder the use of the ATOS-4 approach for an operational mission such as Envisat. The most important factors are interfacing to other systems inside and outside the FOS, and the limitations and characteristics of the internal planning approach itself.

The interfaces depend mainly on operational issues related to the organisation of the mission, and are constraints on the system. For instance, the ATOS-4 planner takes advantage of its integration with the MCS and the power of the controlling application, which can interpret schedules as graphs of activities. The Envisat Flight Operations Control Center is a traditional one, and the Envisat FOS MPS is therefore restricted to schedules of time-tagged command calls. In the same way, the operational concept limits the decisions that can be taken by the planner, and constrain them to operator supervision.

As far as planning is concerned, the ATOS-4 planning approach cannot be considered as a fully generic approach that would be applicable to all areas of Mission Planning. Mission Planning covers a range of problems, which cannot be covered by a single unique approach. Even in the restricted scope of earth observation missions, many complex problems are not addressed in ATOS-4 (e.g. geographic target decomposition versus selection of one temporal solution).

Many of the Mission Planning requirements of a mission such as Envisat are related to the generation of primary activities from external sources, covered partly by the service mechanism and partly by the rule-based system. ATOS-4 concentrates on the generation of secondary activities based on causal dependencies. As such, the areas of Envisat where ATOS-4's approach could be directly applied are limited, e.g.:

- The timeline completion, whereby the gaps between partial plans of primary activities are connected to make a full plan.
- The implementation of highly dependent activity sequences. This is performed in Envisat by specific external routines.
- The derivation of schedules of operational procedures, which is not required for Envisat.

If the Envisat FOS MPS had to be extended in scope for re-use in other missions, the first two applications would surely benefit from extensions in this direction. On the third point, recent evolutions of the Mission Control Systems have focused on the integration of automatic procedure execution to controlling applications, which make the use of a planner is this area more likely in the near future.

From a more general point of view, the current evolution of AI planning systems towards providing solutions to operational planning problems would benefit from making these systems easily available for evaluation in the scope of operational missions. Providing guidance on the potential use that can be made of them with respect to the mission requirements would be an additional step towards the application of these techniques in operations. Working towards more open systems, in order to facilitate their integration to operational infrastructure is another major factor that would make possible the use of advanced techniques in an operational context.

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