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Title : **Advanced Planning and Scheduling Initiative**
Final Report - Executive Summary

Abstract : This document presents the Executive Summary of the Final Report of the Advanced Planning and Scheduling Initiative (**APSI**) Study, which specified the APSI framework intended to enhance operation of ESA's missions by providing an experimental framework to support the development of Artificial Intelligence (**AI**) planning, scheduling and optimisation techniques.

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AMENDMENT POLICY

This document shall be amended by releasing a new edition of the document in its entirety. The Amendment Record Sheet below records the history and issue status of this document.

AMENDMENT RECORD SHEET

ISSUE	DATE	DCI No	REASON
1	31 Aug 2009	N/A	Initial Issue
2	06 Dec 2010	N/A	Updates following review

1. INTRODUCTION

1.1 Purpose and Scope

The projected Advanced Planning and Scheduling Initiative, the APSI Timeline Representation Framework, (**ATRF**) is intended to enhance operations of the European Space Agency (**ESA**) planning and scheduling by providing an AI development platform allowing rapid development of AI based tools for planning, scheduling and optimisation processes. The APSI study established a timeline representation framework with AI techniques and approaches in mind.

This Executive Summary of the Final Study Report

- outlines the background and objectives of the study;
- summarises the work performed;
- provides a top level description of the APSI framework concepts, and
- reviews the documents and outputs produced by the study.

1.2 Structure of the Document

After this introduction, the document is divided into a number of major sections that are briefly described below:

2 BACKGROUND AND OBJECTIVES

This section provides a background to the Advanced Planning and Scheduling Initiative study and an outline of the objectives that the study fulfilled.

3 WORK OUTLINE

A brief outline of the work carried out during the course of the APSI study is given within this section, highlighting the critical stages along the way.

4 CONCEPTS

This section provides an outline of the specification and design of the APSI framework which was produced in the context of the Advanced Planning and Scheduling Initiative study. It also illustrates the concepts behind the APSI and how the system interacts to internal and external entities.

5 OPERATIONAL EVALUATION

Within this section we describe the three test case scenarios used to demonstrate the capabilities of the framework in an operational environment through the production of applications built on top of the framework..

6 CONCLUSION

In this section we give our final conclusion on the study and its outcome.

1.3 Referenced Documents

The following is a list of documents with a direct bearing on the content of this report. Where referenced in the text, these are identified as [n], where 'n' is the number in the list below:

[1] APSI Software Requirements and Architectural Design Document, APSI-SRAD-001-1, Issue 3.0, January 2009

[2] APSI Interface Control Document, APSI-ICD-001-1, Issue 2.0, February 2009

[3] APSI Glossary of Terms, APSI-GLS-001-1, Issue 1.1, February 2009

[4] APSI Technical Note 1 – Case Definitions Document, Issue 1.0, January 2007

[5] APSI Technical Note 2 – State of the Art Technology Assessment, Issue 1.0, March 2007

[6] APSI Software User Manual (SUM), APSI-SUM-001-2, Issue 2.0, January 2009

[7] ESA Ground Segment Software Engineering and Management Guide, Parts A, B, and C, BSSC (2002) 1, Issue 1.0, March 2002

1.4 Definitions of Terms

The following terms have been used in this report with the meanings shown.

Term	Definition
Planning	For the purpose of this document, this means the process of arranging a set of steps into an order that satisfies a number of constraints and criteria, without necessarily providing fixed times for these steps. This differs from the operational meaning of planning which includes fixing of times for the planning steps (i.e. scheduling).
Scheduling	For the purpose of this document, this means the process of taking a previously prepared plan or partial plan and fixing timing information on it, whilst ensuring that the plans constraints are not violated. This process nominally includes optimisation routines.
Timeline	A collections of events/activities with or without durations organised into a chronologically ordered list.

1.4.1 Glossary

The following acronyms and abbreviations have been used in this report.

AI	Artificial Intelligence
AIMS	APSI Integral Mission Scheduler
AO	Announcement of Opportunities
APSI	Advanced Planning and Scheduling Initiative
ATRF	APSI Timeline Representation Framework,
ESA	European Space Agency
ESAW	European Ground System Architecture Workshops
IJCAI	International Joint Conference on Artificial Intelligence
IWPSS	International Workshop on Planning and Scheduling for Space
MrSPOCK	Mars express Science Planning Opportunities Coordination Kit
PDL	Problem Definition Language

RD	Reference Document
XMAS	XMM-Newton Mission APSI Scheduler

2. BACKGROUND AND OBJECTIVES

2.1 Introduction

The usage of AI technology and techniques within the field of planning and scheduling for space is growing. There are already many classical planning and scheduling applications used within the European Space Agency and in other agencies around the world. Some of these being very manual in nature and some being very automated tools. Currently only a handful make use of advanced AI techniques (e.g., Jonsson et al., 2000, Knight et al., 2001, Ai-Chang et al., 2004, Cesta et al, 2007). In most cases these systems and procedures can potentially be enhanced by the use of AI techniques at various stages of the planning and scheduling cycle. This is where the APSI study comes in who's aim is to provide a framework to support the development of new and existing AI technologies within the space planning and scheduling domain by providing a core underlying AI modelling infrastructure.

2.1.1 Study aims and goals

The Advanced Planning and Scheduling Initiative, or APSI, is an ESA's programme to implement AI techniques in planning and scheduling that can be applied generically to different types and classes of space mission operations. The goal of the APSI is twofold:

- On one hand, the initiative is aimed at creating an experimental software framework to improve the cost-effectiveness and flexibility of mission planning support tool development.
- On the other, the APSI strives to bridge the gap between advanced Artificial Intelligence (AI) planning and scheduling technology and the world of space mission planning.

The foreseen final output of the project is a (as much as possible) general software framework for supporting rapid development of AI planning & scheduling prototypes. Moreover the program also includes the development of three different case study prototypes to demonstrate the validity and reusability of the proposed approach.

2.1.2 Project distribution

To make best use of the vast knowledge in the field of AI in the two year period that the study was scheduled for, the project was performed in collaboration with three academic partners, all well versed in the field of AI planning and scheduling techniques. VEGA was prime contractor in the study overseeing the whole project with the academic partners sub-contractors being ISTC-CNR (based in Rome, Italy) ONERA (based in Toulouse, France) and Politecnico di Milano (based in Milan, Italy). The initial phase of the project consisted of a collaboration on all fronts to establish a common knowledge base of the problem domain and a common understanding of how we could represent and model these ideas. ISTC-CNR then had the responsibility to develop these ideas into the framework and underlying structures of the model. In parallel to this, VEGA and ESA researched, selected and defined possible scenarios from present and future missions that could be useful candidates for basing test case scenarios on for which demonstration tools would be developed. In the second phase a set of case scenario tools was to be developed, one after the other, making use of the developed framework and where necessary feeding back additionally required functionality into the framework. Each of the academic partners were responsible for the development of a single test case scenario, which were developed one after the other and focusing on different selected target missions. For this to succeed the main APSI framework had to be put into place.

3. WORK OUTLINE

The study was performed over a period of two and a half years and was broken down into several main components which have been summarised in the following :-

- Test Case Scenario Investigation and Definition
  - Investigating and defining mission scenarios that could be potentially used to demonstrate the capabilities of the framework by means of prototype test tool implementations.
- State of the Art technology assessment
  - An assessment of the current state-of-the-art technology taken from the current state of AI technologies and from the knowledge backgrounds that each of the partners brought into study.
- Framework concepts design
  - In-depth deliberations within the consortium over what would be needed in a framework that could support AI technologies and how this could be best realised. Ontology's were discussed, proposed and reviewed culminating into the implemented framework.
- Framework implementation and review
  - The implementation of the APSI framework was carried out in an iterative approach using the feedback and experience from within the consortium to shape the results. This was combined with internal review cycles following each updated release of the framework. Demonstration test routines were produced to illustrate the functionality of the APSI framework and its concepts at each stage. The implementation also included the production of design documentation and source code JavaDoc documentation to assist in the future development of the APSI framework and tools built using the framework.
- Selection of test case scenarios
  - Each demonstration test case was selected using the scenario definitions document as input. For the selection, the scenarios applicability to the framework functionality to be demonstrated was taken into account, along with the availability of mission specific input data and support from mission specialists for the test case tool to be successful.
- Implementation of selected test case tools
  - The three demonstration test case tools were developed following on from each other. The first demonstration test case tool (Mars express Science Planning Opportunities Coordination Kit (**MrSPOCK**)) was based on the Mars Express long-term planning of pericentre science opportunities, uplink opportunities and maintenance windows. It used a genetic algorithm as the solving method to produce the resulting optimised plan. The INTEGRAL long-term science planning problem was used as the focus for the second demonstration test case tool (APSI Integral Mission Scheduler (**AIMS**)) which employed stochastic heuristics, stochastic hill climbing, local search, restarts and tabu lists to

generate its resulting schedules. For the final demonstration test case tool (XMM-Newton Mission APSI Scheduler (**XMAS**)) the XMM-Newton long-term planning of science observation was selected. The tool itself was based on the second test case tool with extensions added to support the mission specificities and the missions global constraints. These extensions included the use of a multi-criteria reasoning function and the inclusion of chained observation types.

- Updates to framework reflecting feedback from test cases
    - Updates were made to the framework during the development of the three demonstration test case tools as new concepts and unforeseen functionality was required. These updates also covered bug fixes to the core framework when they were discovered.
- A successful Final presentation of the APSI framework and the three demonstration test cases was given at ESOC on the 19th June 2009 with all project partners, test case tool users from ESAC/ESOC and the ESA technical officer for the project participating.
- An extension to the original work to produce a mature set of documentation for the framework in the form of a framework user manual with alignments to the SRAD and Javadoc documentation. In the course of this work additional example java classes, domain definitions and problem definition files have been produced to give more elaborative demonstrations of how the APSI framework can be utilised.

3.1 Paper list

In addition to these the consortium have produced and presented several working papers on the framework and the three demonstration test case tools at prominent workshops and conferences worldwide to promote the work performed on behalf of the agency. These included SpaceOps 2008, the European Ground System Architecture Workshops (**ESAW**) 2009, the International Joint Conference on Artificial Intelligence (**IJCAI**) 2009 and the International Workshop on Planning and Scheduling for Space (**IWPSS**) 2009.

The following table lists all the conferences, workshops and other events that the APSI project partners have presented papers at in one form or another as at the date of this document.

Conference/Workshop	Date	Paper/Presentation Title
SpaceOps 2008, Heidelberg, Germany	19 June 2008	APSI
IJCAI 2009, Pasadena, USA	July 2009	Advanced Planning and Scheduling Initiative: MrSPOCK AIMS for XMAS
ESAW 2009, Darmstadt, Germany	May 2009	Advanced Planning and Scheduling Initiative (APSI): MrSpock AIMS for XMAS in the space domain
IWPSS 2009, Pasadena, USA	July 2009	Advanced Planning and Scheduling Initiative: MrSPOCK AIMS for XMAS in the space domain

Conference/Workshop	Date	Paper/Presentation Title
IWPSS 2009, Pasadena, USA	July 2009	MrSPOCK: Long-term Planning for the ESA Mars Express Mission
IWPSS 2009, Pasadena, USA	July 2009	AIMS: A Tool for Long-term Planning of the ESA INTEGRAL Mission
IWPSS 2009, Pasadena, USA	July 2009	Advanced Planning and Scheduling Initiative's XMAS tool: AI for automatic scheduling of XMM-Newton long term plan
DASIA 2009, Istanbul, Turkey	May 2009	AI TECHNIQUES FOR SPACE : THE APSI APPROACH
SPARK-08, Sidney, Australia	July 2008	Looking for MrSPOCK: Issues in Deploying a Space Application
IAAI-09, Pasadena, USA	July 2009	Developing an End-to-End Planning Application from a Timeline Representation Framework
Computational Intelligence,		MrSPOCK: Steps in Developing an End-to-End Space Application

4. CONCEPTS

4.1 The framework concept

The APSI framework follows the timeline-based approach which has been proposed in (Muscettola et al 1992), since then used in a number of space related tools (e.g., Jonsson et al., 2000, Chien et al, 2000) and studied in several works (e.g., Frank and Jonsson, 2003). In particular the APSI framework uses the generic term of "component" to identify a modelling primitive that refer to feature endowed with a temporal behaviour. Specific example of components in the framework are the multi-valued state variables, a-la (Muscettola et al 1992), and the resources, a-la (Cheng & Smith, 1994). At implementation level the APSI framework is broken down into several functional layers.

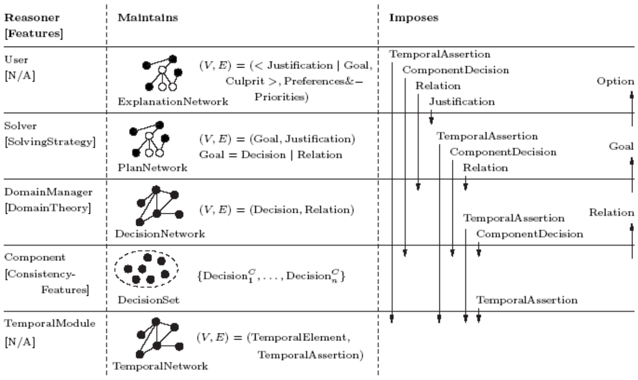


Figure 1: Hierarchy of Reasoners in APSI

It uses components to represent the problem domain that can be reasoned on. In conjunction with this it provides two forms of consistency features that can used to define the characteristics of the domain. These are the value duration feature, used to represent the allowed upper and lower bounds of a duration for a given state variable value, and the transition constraint, used to define the possible permitted transitions among values of a given state variable. This allows for the definition of the correct physical behaviour between them.

More is needed than just the definition of state variables and consistency features to model a given Space related problem. We also need to define how the various components interact with each other within the system. These inter-component relationships are realised within the APSI modelling framework by specficing what is commonly known as the domain theory. A domain theory can be seen as collections of synchronisations or rules which define the consequences of a component's values based on the values taken on by other components defined within the model.

The core of the framework can be seen as comprising of five reasoning layers, these are the User layer, the Solver layer, the Domain management layer, the Component layer, and the TemporalModule layer (see Figure 1). The term User here can refer to a physical human user or another process or system.

The TemporalModule layer provides functionality to compute the effects of temporal assertions over a set of temporal elements within the framework. Being at the bottom of the hierarchy, the TemporalModule layer does not impose any assertions on reasoners at higher levels within the hierarchy. It also does not pass back any assertions either. Its main functionality is to maintain a data structure, a hyper-graph, that contains temporal elements as nodes and temporal assertions as edges of the graph.

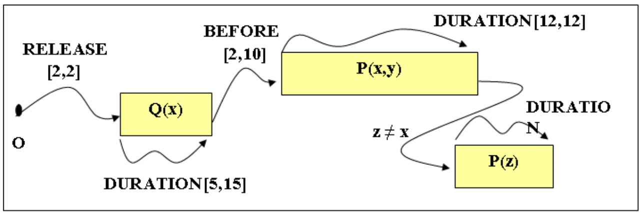


Figure 2: a network of decisions

The Component layer is used to compute the effects of component decisions over a set of Behaviours. It can also impose or retract temporal assertions on temporal elements. Consistency features of the component can be used to distinguish which behaviours are consistent and which are not. The result of which can be passed back to its higher levels detailing the relationships among component decisions that have been used to update the component's behaviours.

In the next layer, the Domain management layer, the effects of relationships over a set of component decisions is computed. The Domain management layer maintains a decision network data structure that represents a hyper –graph of component decisions representing the nodes and the relations between them representing the edges of the graph as can be seen in Figure 2. As with the Component layer, the Domain management layer can impose or retract temporal assertions on temporal elements. In addition to this it can also impose or retract component decisions on components. The Domain management layer also has associated with it a Domain theory. It can use this domain theory to distinguish which of its evolutions are consistent and which are not. Using this theory it can determine sub-goals and pass back to the higher levels goals that must be achieved. Figure 3 illustrates a set of state variable and the domain theory imposed on these variables.

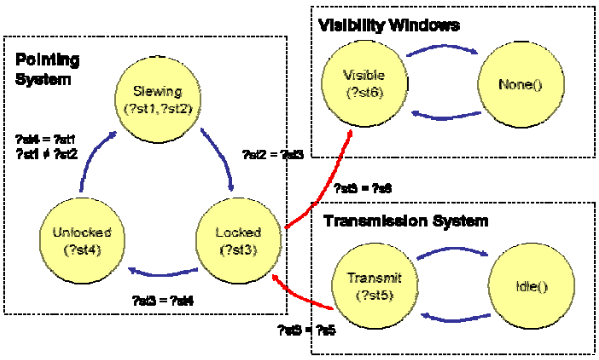


Figure 3: The Pointing System state variable and Domain Theory

Within the Solver layer the tracking of justifications is performed. Justifications are essentially a grouping together of a set of goals, which are in turn made up of either Component decisions or relationships between Component decisions. The Solver layer, like the previous layers, also maintains a hyper-graph data structure to represent the plan network. In this case the nodes are Goals and the hyper-edges are the Justification. The plan network describes the solving decisions taken by the solver, each of these solving decisions being a hyper-edge connecting a subset of goals in the network. As with the previous layers the Solver layer can impose and retract features of the previous layers. In addition to this it can also impose and retract relationships on sets of Component decisions. The Solver layer contains a solving strategy that guides it in the building of the Plan network by making decisions, for instance, on how to impose relationships between component decisions on the lower levels. The results of these decisions being reported back to the higher levels as forms of options that can be taken.

The highest level of the hierarchy is the User layer. Here we specify the goals of the solution which can be seen as justifications by the Solver layer. As with the Solver layer, the User layer can also impose relationships between component decisions, component decisions over components and temporal assertions over temporal elements. Within the context of the APSI, this reflects the assumption that Users can contribute to the solving process in various degrees, either by specifying Goals or invoking the lower level entities directly. In this way the Users contribute to maintain an explanation network, which is again, as in the previous layers, represented as a hyper-graph where nodes are Justifications or single goals annotated with a culprit which identifies "who decided the Goal/ Justification" and edges are the preferences & priorities through which relations between the nodes can be expressed. In this context, Preferences and Priorities signify the achievement of a Goal or groups of Goals.

Within the APSI framework these concepts are realised as a set of packages containing classes corresponding to the reasoning layers describe above.

4.1.1 Technology

The framework is based on existing theories and approaches developed in the academic arena. The philosophy underlying the *Timeline-based Planning and Scheduling* is inspired by classical Control Theory, in that the planning and scheduling problem is modelled by identifying a set of **relevant features** whose temporal evolutions need to be *controlled* to obtain a desired behaviour. In APSI such problem features are called **components** and are the primitive entities for knowledge modelling. They represent logical or physical subsystems whose properties may vary in time. An intrinsic property of components is that they evolve over time, and that control decisions can be taken on components to define their evolution.

APSI is designed around the concept of **model based components.** Components model different temporal behaviour over time based on a set of constraints while modelling the physical world. The problem solving task is of selecting a temporal behaviour of the conglomerate of components of the domain modelled that satisfy all requirements including current **mission goals**. It uses a state value representation with a state propagation mechanism which uses a behaviours based approach to guide the propagation of state values through a timeline.

The architecture used to realise this framework and construct the required mechanisms is Java. This allows for easier portability between different platforms.

4.2 Validating the framework

To validate the framework and its applicability to space based problems, it was required that three test case scenarios be defined and selected with resulting tools, built on top of the framework, being produced. The objectives of these case tools being to identify missing functionality within the framework that would need to be added and to demonstrate that the framework could support the modelling of various classes of problems found within the space domain. In support of this, it was necessary to obtain support from the operational staff of the missions that the cases were being based on.

5. OPERATIONAL EVALUATION

5.1 Introduction

The validation and verification of the APSI framework was carried out in the form of three demonstration test case tools.

5.2 APSI Timeline Representation Framework software

This is the main output of the study and consists of a functional timeline representation framework allowing the modelling of mission elements and constraints through the use of a domain definition language, state variables and state resources. A software user manual (see [6]) was also produced to accompany the APSI framework and test case tools.

5.3 Test Case Tool results

5.3.1 MrSPOCK – Mars Express

An application was developed to support the Mars Express planning team at ESOC in the generation of the initial long-term planning of uplink opportunities, maintenance windows and nadir pointing science opportunities.

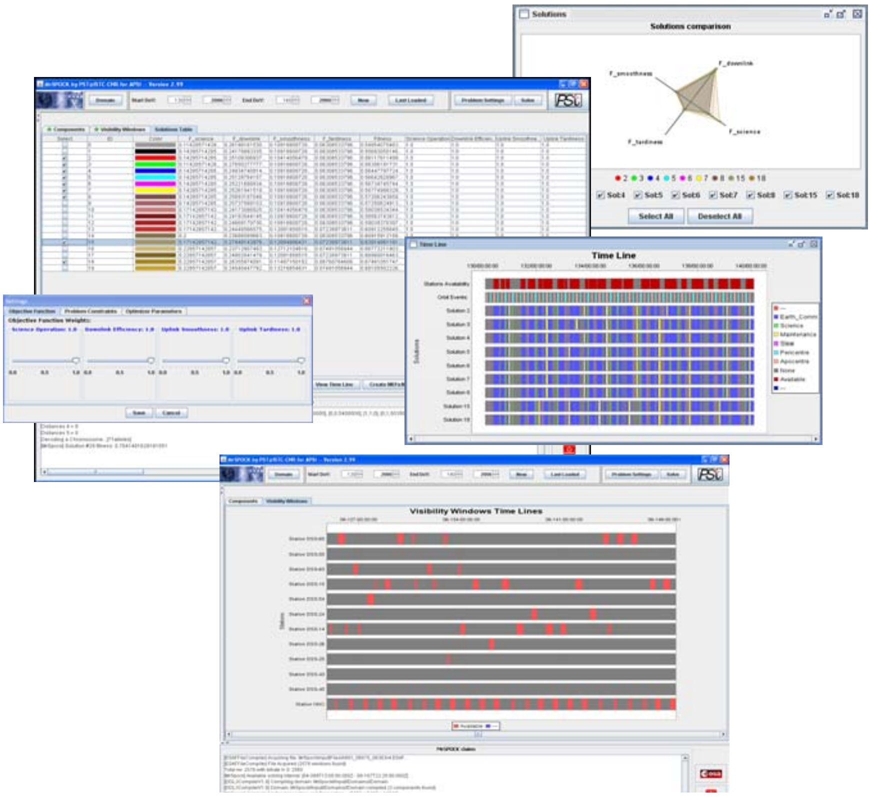


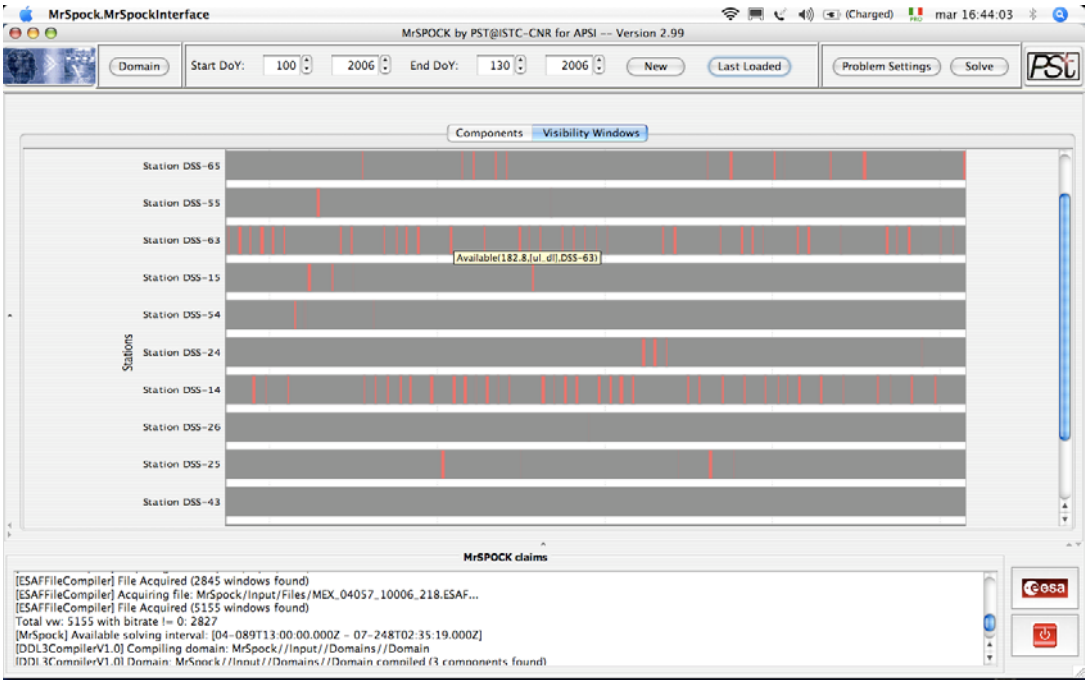
Figure 4:MrSPOCK results and user interface

The first case selected to be developed by the project has been supported by the Mars Express mission planning team based at ESOC in Darmstadt, Germany. It is aimed at the pre-optimisation of the long term planning of maintenance windows and downlink opportunities during the nominal Medium Term Planning (MTP) cycles with the Planning and Scheduling Team (PST). The Mars Express satellite is a scientific observation platform with optical and non-optical instruments used to observe the planets atmosphere, surface and sub-surface structures. It orbits the red planet approximately every 6.5 hours, making scientific observations at various points in it's path. Most observations are carried out at pericentre when it is nearest to the planets surface and over a period of about 68 minutes around pericentre.

The optimization procedure used for MrSPOCK has been based on *Genetic Algorithms* (GA). GA is a well-known and effective computational paradigm for function optimization inspired from the study of population genetics. This was considered an appropriate approach due to the multi-objective nature of the planning problem. Indeed the GA is combined with a constructive heuristic procedure that instantiate the temporal plan which represent the complete and detailed output of MrSPOCK.

5.3.1.1 APSI Case #1 Prototype Software – MrSPOCK

This was the first of the three test case tools developed under the project to demonstrate and validate the concepts used within the framework itself. The test case was based on a Mars Express long term planning scenario requiring the allocation and optimisation of maintenance windows, uplink windows and pericentre science observations. Instructions on how to use the tool were produced and included in the software user manual (see [8]). Optimisation was performed by using a genetic algorithm to derive the plan from an initial population. The tool was successfully deployed to the Mars Express Mission Planning Team at ESOC in Darmstadt for operational evaluation.



5.3.2 AIMS – INTEGRAL

An application was developed to support the INTEGRAL science planning team at ESAC in the generation of the initial long-term science observation planning for Announcement of Opportunities (**AO**).

Figure 5: AIMS results and user interface

In the second case we obtained the support from the INTEGRAL (INTErnational Gamma-Ray Astrophysics Laboratory) long term planning team of the Integral Science Operations Centre (ISOC) based at ESAC in Madrid, Spain. The INTEGRAL mission, an ESA mission managed in cooperation with Russia and the USA, aims at observing gamma-ray emissions from regions of the universe whilst revolving around the earth in a highly elliptical orbit. Each revolution lasting 72 hours in length of which only 58 hours can be used for observation time due to the effects of the Earth's radiation belt. The satellite itself holds four instruments for observing space regions which are all fixed in the same direction.

The main aim of the tool is to optimise the satisfaction of the scientific objectives expressed in the yearly announcements of opportunities. These announcements of opportunities, or AO's as they are commonly called, are generated by the user community prior to the commencement of the next long term planning period which nominally covers one year. Not only do AO's for the next planning period have to be considered but also AO's from the previous planning period which were not scheduled are included, albeit with a higher priority than previously.

To solve this optimisation problem, the tool uses a local search algorithm that combines the best ideas from the state-of-the-art local search algorithms such as hill-climbing, tabu search, and simulated annealing. This local search algorithm uses the underlying APSI framework to maintain flexible consistent schedules within each revolution and to determine the amount of observation time that can be added to the observations already scheduled within a revolution. In other words, the APSI framework is used to efficiently manage the basic scheduling constraints and the local search algorithm, built on top of it, is used to manage the optimization criterion and specific constraints.

5.3.2.1 APSI Case #2 Prototype Software – AIMS

The second of the three test case tools was developed and based on the INTEGRAL long term planning of science observations covering the complete announcement of opportunities (typically 1 year). It makes use of various AI techniques (such as stochastic hill climbing, stochastic heuristics, local search, tabu lists and restarts) to produce the science plans. The tool was successfully deployed to the INTEGRAL Science Planning Team at ESAC in Madrid for operational evaluation.

5.3.3 XMAS – XMM-Newton

An application was developed to support the XMM-Newton science planning team at ESAC in the generation of the initial long-term science observation planning for Announcement of Opportunities.

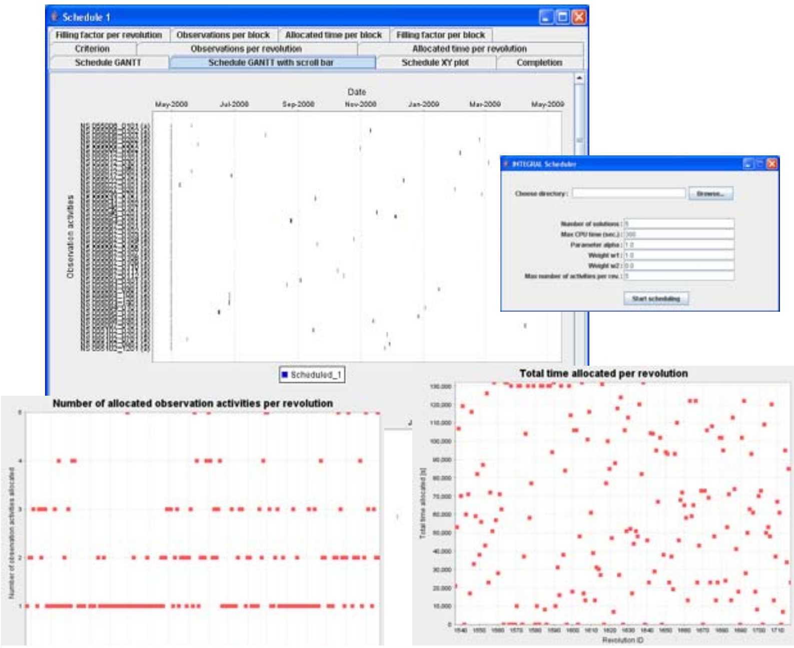


Figure 6:XMAS results and user interface

For the third and final test case scenario, the support of the XMM-Newton long term science planning team was obtained also based in ESAC, Madrid. The XMM-Newton satellite was launched in 1999 with the aim of providing a space-based X-ray observatory that is open to the scientific community. Like INTEGRAL, XMM-Newton also has a highly elliptical orbit around the Earth but lasting only 48 hours per revolution. Within these 48 hours, and again due to the Earth's radiation belt, only ~36 hours of the revolution are usable for observation time.

Following detailed analysis of the XMM-Newton planning problem, it could be seen that the planning required was very similar to that developed for the INTEGRAL tool. There were some subtle differences between the two missions though. Long-tern planning for the XMM-Newton mission required a more dynamic initial plan with a lower filling factor to allow for the provision of short term changes to be made to the plan without major re-planning of the long-term plan. For these reasons it was decided to take the most current release of the AIMS tool at the time to base the case #3 development upon. In the process, aligning the input file formats between the AIMS tool and those needed for the XMAS tool, creating a common set of input file formats.

5.3.3.1 APSI Case #3 Prototype Software – XMAS

For the third of the three test case tools, development reused the AIMS tool making extensions in a generic way to accommodate the peculiarities of the target mission. The target mission was the XMM-Newton long term planning of science observations covering the complete announcement of opportunities (typically 1 year). These enhancements to the AIMS tool include the implementation of a multi-criteria evaluation function and the notion of chained observations. The tool was deployed to the XMM-Newton Science Planning Team also based at ESAC in Madrid for operational evaluation.

5.4 Known limitation of the APSI framework

5.4.1 Development architecture

The prototype has been developed using the Java programming language. Even though this gives it great flexibility for reuse on many architectures and operating systems, this also means that the framework is not currently usable directly onboard spacecraft. The concepts can be re-engineered using a programming language that is suitable for current onboard usage but this was out of the scope of this study.

5.4.2 Performance

Measuring the real performance of the system requires more research as it is not a simple task. The performance of the test case tools depends a lot on the dimensions of the problems to be solved. The more variables that have to be considered and the more conflicting constraints a problem has the more complex it is to find a solution and hence the longer it will take to compute the solution, if one can be found.

6. CONCLUSION

We have shown you a brief glimpse of the APSI framework and touched lightly on the three test case scenario tools that have been developed to demonstrate the capabilities of the framework.

- APSI can assist in the development and integration of AI techniques within the planning and scheduling for space domain by providing an underlying framework that facilitates the modelling of planning and scheduling problems.

- Tools can be built upon this framework to support existing applications and technologies, or to create and test new innovative AI techniques and technologies.

We do not proclaim that the APSI framework is suitable to every situation of a space planning and scheduling problem or that it is a complete framework that can be used of the shelf. There are always additional concepts that could be developed and evolved within the framework. As new technologies emerge within the AI field so must the APSI framework to include these. To cope with this aspect, one of the main characteristics of the APSI framework is its flexibility (via a plug-in based schema) that allows enriching it with new functionalities and/or modules.

The considerations on the realization of the three prototypes suggest a general schema for implementing domain-specific decision support tools, namely:

1. implement any additional component types that are required by the application context

2. extend and/or tune the general solving procedure where necessary

3. define a model where the component types are instantiated with domain-specific characteristics and are logically bound by synchronizations

Of course, these three steps cannot alone provide a complete deployable software tool. Nonetheless, they provide a means to reduce the gap between prototype and final application by factoring away all the major algorithmic and modelling design choices.

6.1 Lesson Learnt

Several lessons could be gained from this study:

- Working with the end users of the product early on in the game allows for the product to be guided by their actual needs. Short development and discussion cycles with the end-users helps to maintain the path to the project goal.

- Collaboration of academia and industrial partners helped to bridge the gap between the space world and the academics. Additional effort is needed to support these initial bridges in future projects to further the collaboration between space, industry and academia and to strengthen this emerging structure.

6.2 Further work

Future activities foresee, starting from the results of the current project, to extend the APSI framework with respect to the following principal directions:

- Consolidation of the physical and source code documentation of the APSI Timeline Representation framework to ensure a concise and complete set of reference material to assist future developments based on or making use of the framework. Additionally, producing a set of initial requirements specifying a Problem Definition Language (**PDL**) for future development and incorporation into the APSI framework.

- Consolidation of the Modelling Framework: this activity entails the formalization of the modelling framework and characterization of its expressiveness. Also, to extend the modelling framework to address uncertainty of the effects of actions and partial observability.

- Consolidation and extension of the internal data representation and algorithms. In particular, to extend the underlying APSI framework domain and problem representation in order to support the additional planning algorithms. Also, providing a methodology to handle hard/soft constraints in the framework (e.g. integration of soft constraints in the optimisation criterion).

6.2.1 APSI Software Requirements and Architectural Design document

This document captured the requirements of an AI based planning and scheduling system from the point of view of an operational environment, illustrating what would be needed for a fully fledged application. The framework and the three test case tools concentrated only on a subset of these requirements to be implemented.

6.2.2 APSI Technical Notes ([4] & [5])

Two technical documents were produced for the APSI study. The first containing the assessment and understanding of the state-of-the-art technologies used within the field of AI planning and scheduling. The second covers the investigation and definition of scenarios which were considered for implementation during the development of the three framework validation test case tools.

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