Towards intelligent assistants for space operations and logistics

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ABSTRACT

This paper describes the Intelligent Support to Logistics concept (ISL), that is emerging at MATRA MARCONI SPACE thanks to software tools of the OPSWARE family. These tools provide support for project and mission planning/scheduling, operations procedures elaboration/validation/execution, generation and browsing of operations manuals, monitoring/trend analysis and reporting, failure diagnosis. They are based on advanced software engineering techniques, including AI techniques. Several instances of these tools have been fielded with a very significant pay-off, both at MMS and at external customers' sites (ESA, CNES, ARIANESPACE).

I. INTRODUCTION

The complexity and extended life duration of modern spacecrafts, and the resulting risks of potential human errors and of inaccessibility of skilled personnel, together with productivity enhancement requirements, call for the automation of many spacecraft operation tasks.

Over the last seven years, MATRA MARCONI SPACE (MMS) has developed, together with European partners, some software applications for operations preparation and operations execution (spacecraft monitoring and commanding) that deal with these problems and are now used in operational environments [4, 5]. These applications are based on advanced technologies from computer science (artificial intelligence, knowledge acquisition, computational linguistic, human factors engineering, operations research, object oriented programming, hypertext techniques...). A key point is that each application has been developed in close cooperation with operations engineers of MMS and of MMS customers (ESA, CNES, ARIANESPACE) in order to meet their requirements.

The OPSWARE concept is a synthesis of that development effort, a view of the activities centred around conventional operations and data processing systems
as a consistent set of well defined tasks that can be automated thanks to software applications providing intelligent assistance. These tasks include planning/scheduling for mission management and for logistics, operations procedures elaboration/validation/execution, generation and browsing of operations manuals, monitoring/trend analysis and reporting, failure diagnosis. Each task corresponds to a generic software tool that can be easily adapted to develop a new application.

The initial motivation for OPSWARE was to support space operations preparation and space operations execution. However, users' feedback is demonstrating that OPSWARE tools may have a much larger impact. In fact, this kind of tool may be used in all the phases of a space programme and thus can have a large impact on logistics.

Like many other domains, space activities are moving from a product oriented field to a service oriented field. This trend affects both space institutions and prime industrial contractors. For example, some space programs tend to be considered as a packaged service to a scientific community, or a service to a telecommunication operator. One of the main concerns is now to maximise customers satisfaction by increasing the availability of the service while reducing the cost of the space system, the maintenance costs and the development time. These performance improvement goals require an industrial, optimised, approach for the development phase of a space system as well as for the operation/maintenance phase.

MMS has already integrated these facts and has been implementing logistics methods as a way to optimise its activities. This paper describes a new approach to logistics tools that is emerging at MMS, the Intelligent Support to Logistics concept (ISL) that is based on the OPSWARE concept.

It is clear that OPSWARE tools must be associated with work methods to become effective, and ISL is just one possible method. There are probably many other approaches that can take advantage of these tools, inside and outside the space domain.

The main problems that MMS logisticians are addressing are summarised in Chapter II. Chapter III describes the OPSWARE tools and Chapter IV describes the Intelligent Support to Logistics concept based on the tools. Chapter V demonstrates how the ISL concept could meet the expectations of logisticians that are described in Chapter II.

II. THE NEW REQUIREMENTS OF SPACE LOGISTICS

It is clear that reduced space budgets and competitive markets call for improved methods and tools. However there are other trends that seem to emerge in the space domain:

- end users requirements are getting more and more critical (telecommunication, TV, observation, strategic systems): this implies more reliability of systems and a strong reactivity to problems.
- complexity of spacecraft and ground systems is increasing and thus the complexity of operations also. Ground systems are moving towards distribution, greater functions and a lot of new technologies.

- the amount of written information and data bases is increasing dramatically.

- life duration of systems is extended: technical memory and training of new personnel is a major concern. Preventive maintenance and spacecraft monitoring must be systematised.

For logisticians these general facts can be translated into the following requirements:

- harmonize tools and methods used in development, Assembly Integration and Validation (AIV), and Operations.

- guarantee information consistency.

- make sure that documentation is in line with the system state.

- capitalise knowledge and technical memory.

- facilitate knowledge transfer and training.

- provide assistance to operators (monitoring, decision making, diagnosis).

- monitor, check, verify system aging on long periods of time.

- anticipate and plan activities.

- react quickly when a problem occurs.

III. THE OPSWARE CONCEPT

The complexity of space operations, and the cost of a wrong manipulation often requires the close cooperation of man and machine rather than autonomous systems. The OPSWARE concept is a view of the activities centered around conventional operations and data processing systems, as a consistent set of well defined tasks that can be automated thanks to software applications providing intelligent assistance.

OPSWARE has lead to a consistent set of generic software tools that correspond to all the facets of Figure 1.

The OPSWARE concept is the synthesis of more than seven years of work during which MMS has developed, together with European partners, some operational or pre-operational software applications as listed in Figure 2.

The next step was to derive from these various applications a set of generic tools, OPSWARE, that are now becoming available to implement new applications in a very efficient way. MMS focuses on genericity and reusability so that each tool can be customised easily to a new problem.
The motivation for the generalisation effort, undertaken by MMS to derive OPSWARE from various applications, was to automate similar tasks. For instance the OPSMAKER tool can be used to create and validate operations procedures of telecommunication satellites as well as earth observation satellites. It may be the case that the generalisation will also permit to bridge the gap between very different projects. For example it turns out that OPSMAKER is also suited for the generation of crew procedures and for the generation of maintenance and reconfiguration procedures in a data processing center. Another example is the fact that X-ANALYST can address both problems of analysing the telemetries of a telecommunication satellite and those of an ARIANE launcher.

1. Mission Planning and Scheduling

The PlanERS planning tool was used by ESA/ESTEC engineers in 1991 for testing various mission strategies of the ERS-1 earth observation satellite [6]. The main features of the system are:

- very flexible planning functions thanks to an object-oriented representation of the domain (satellite, resources...) and a rule-based representation of the mission strategies (e.g. on-board recorder management).
<table>
<thead>
<tr>
<th>OPSWARE FACET</th>
<th>CUSTOMER</th>
<th>APPLICATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>MISSION PLANNING &amp; SCHEDULING</td>
<td>ESA/ESTEC</td>
<td>PlanERS FOR ERS-1 EARTH OBSERVATION SATELLITE MISSION STRATEGY DEFINITION AND SIMULATION</td>
</tr>
<tr>
<td>LOGISTICS PLANNING &amp; SCHEDULING</td>
<td>MMS</td>
<td>ARIANE 4 EQUIPMENT BAY ASSEMBLY, INTEGRATION &amp; VALIDATION</td>
</tr>
<tr>
<td>INTELLIGENT ON-LINE DOCUMENTATION</td>
<td>MMS</td>
<td>COMMUNICATION SATELLITES OPERATIONS MANUAL</td>
</tr>
<tr>
<td>PROCEDURES ELABORATION &amp; VALIDATION</td>
<td>CNES, MMS, ESA</td>
<td>POM TOOL FOR TELECOM2, HISPASAT &amp; SOHO PROCEDURES ELABORATION</td>
</tr>
<tr>
<td></td>
<td>ESA/ESTEC</td>
<td>PREVISE TOOL FOR MANNED FLIGHT PROCEDURES ELABORATION &amp; VALIDATION (SPACELAB, COLUMBUS)</td>
</tr>
<tr>
<td>PROCEDURES EXECUTION</td>
<td>ESA/ESOC</td>
<td>EXPERT OPERATOR ASSOCIATE TOOL FOR MARECS B2 SPACECRAFT OPERATORS ASSISTANCE</td>
</tr>
<tr>
<td></td>
<td>ESA/CNES</td>
<td>CREW SUPPORT SYSTEM FOR ASTRONAUTS ASSISTANCE &amp; TRAINING</td>
</tr>
<tr>
<td>INTELLIGENT MONITORING &amp; DATA ANALYSIS</td>
<td>ARIANESPACE</td>
<td>ARIANEXPERT FOR ARIANE 4 POST-FLIGHT DATA ANALYSIS</td>
</tr>
<tr>
<td></td>
<td>MMS</td>
<td>TELECOM2 &amp; HISPASAT SATELLITES PERFORMANCES ANALYSIS</td>
</tr>
<tr>
<td>FAILURE DIAGNOSIS</td>
<td>CNES</td>
<td>TELECOM2 FAILURE DIAGNOSIS</td>
</tr>
</tbody>
</table>

Figure 2, OPSWARE applications developed by MMS.

- high performances: on a medium size work station, the system can handle more than 4000 requests in less than 30 minutes with an average computation time of about 10 seconds per orbit.
- an environment that allows end users to define and update mission strategies, thanks to a custom language and its associated syntax driven editor.

PlanERS allowed the identification of the appropriate mission strategy for optimising mission products, and thus customer's satisfaction. Part of the Man Machine Interface is shown on Figure 3.

Figure 3, a screen of the PlanERS planning system: a schedule of various activities on board the spacecraft (modes of some sub-systems), ground station visibility and resource consumption (e.g. power) are displayed.

2. Operations Planning and Scheduling

The OPTIMUM planning tool has been originally developed for spacecraft Assembly Integration and Verification planning, scheduling and plan repair [1].

- The comparative advantage of OPTIMUM, with respect to other systems, is its ability to capture information which describes the underlying logic of the plan, instead of using pre-defined sequences of activities. This allows the system to verify the logic of the plan built or updated by the user.

The main features of OPTIMUM are:

- a hierarchical description of the project structure.

- an editor to define in a simple way complex resource requirements and resource availability profiles.
Artificial Intelligence in Engineering

- planning & scheduling rules.
- advanced features to ensure the quality of the plan.
- assistance in monitoring and plan repair.
- reporting tools.
- interface with a DBMS.
- interactive graphical interface to edit PERT graphs, hierarchical structure of activities, and GANTT diagrams.

OPTIMUM is currently used at MMS for logistics planning of the assembly activities of the Ariane 4 equipment case.

3. Intelligent On-line Documentation

MMS has implemented an advanced system for editing and browsing the operations manual of communication satellites.

This tool is based on a data base that guarantees safe concurrent access to the document by the various engineers preparing the documentation. The tool is also integrated with the system data base that includes the definition of various parameters including telecommands and telemetries. Hypertext techniques permit efficient browsing through these large documents.

4. Procedures Elaboration and Validation

Most of the activities that require commanding a very complex system like spacecraft are based on formalised procedures that are written and validated in advance. Generally the specialists who generate these procedures are different from the operators who follow them. Procedures record possible command sequences and checks to be done, in a way that facilitates real-time decision making and prevents errors from the operators.

The POM tool has been developed by MMS to support the generation and maintenance of satellite ground control procedures, and to facilitate their use during operations thanks to a procedure browser [8]. POM is now used operationally for the procedures of the Telecom 2, HISPASAT and SOHO spacecrafts.

From the experience of the various procedures management tools developed in the last four years (including the POM, EOA and CSS projects [7]), MMS has derived OPSMAKER, a generic tool for procedure elaboration and validation.

Based on a formal computerised representation of procedures, the main features of OPSMAKER are:
Artificial Intelligence in Engineering

- a generic kernel for operations procedures verification, formatting and execution, based on a procedure compiler that detects syntactic errors in procedures.

- a customised procedure editing environment based on a syntax-driven editor and a database that allows concurrent access to information (client-server architecture) for safe team work.

- an advanced procedure formatter for procedures display and printing, based on a standard word processor that generates high quality documents.

- an advanced procedure checker, based on qualitative simulation, that provides a rich set of verifications (syntactic, local, temporal, logical,...) to speed up procedure development: simple errors are detected early before starting detailed and complex simulations.

The first OPSMAKER applications are PROCSAT (sponsored by CNES) for SPOT 4 procedures, and PREVISE (sponsored by ESA/ESTEC) for manned flight procedures (Spacelab, Columbus).

Figure 4, OPSMAKER procedure editor: once a procedure has been entered, it can be verified by the system and then automatically formatted to a high quality document.
5. Procedures Execution

The Expert Operator Associate (EOA) is a prototype real-time interactive support system for satellite control operators [7, 9].

EOA is based on a formal representation of operations procedures such as those produced by OPSMAKER. These procedures can be executed by the system in a semi-automatic mode. EOA also provides functions for alarm filtering, emergency procedures selection and operations scheduling.

The system is connected to the ESOC control centre (MSSS) and implements a significant part of the Flight Operation Plan of the MARECS-B2 satellite. It is under experimentation at ESA/ESOC. Such a system should permit to increase operations safety and efficiency to face increasing spacecraft complexity and reduced availability of operations experts.

6. Intelligent Monitoring and Data Analysis

The X-ANALYST tool enables the standardisation of the data analysis process through the formalisation of the data analysis procedures, and the build-up of a "technical memory" for a given project.

![Figure 5, a screen of the X-ANALYST data analysis tool: analysis procedures are formalised, a report is automatically generated.](image)
X-ANALYST has been derived from the ARIANEXPERT tool that has been operational at ARIANESPACE since January 1991 for the post-light analysis of the ARIANE 4 launcher [2].

Its main features are:

- a rich set of signal processing and graphical tools.
- a procedure-based analysis definition.
- a tree-based procedures conditional chaining.
- flexible syntax-driven and graphical editors.
- the generation of a technical memory (archiving of all analysis results).
- automatic report formatting through a word processor.

The measured benefits of ARIANEXPERT are significant: the analysis duration is reduced by 75% while the analysis is more detailed and goes further than previously and the analysis is more exhaustive and more systematic.

X-ANALYST is being adapted to the analysis of MMS communication satellites telemetry.

7. Failure Diagnosis

DIAMS is a diagnosis expert system derived from the TELECOM 2 EXPERT SYSTEM developed for CNES [3].

A first complete version of the system has been available since June 1992, and the system was formally delivered to CNES in January 1993.

It is a failure diagnosis tool based on various types of knowledge covering the entire TELECOM 2 satellite: decision trees encoding the global spacecraft behaviour, and a collection of subsystem functional models capturing the detailed links and interactions that exist between the various spacecraft components.

This system is also considered by CNES as an efficient training tool, thanks to its deep knowledge of the spacecraft and thanks to the possibility of session replay.

It is also viewed as generating a mission technical memory, allowing the integration of in-orbit experience.

Its main benefits are related to expertise transfer from spacecraft designers to spacecraft operators, and to in-orbit experience capture (a critical point, if we consider the important turnover in operations staff).
IV. LOGISTICS IN THE CONCURRENT ENGINEERING FRAMEWORK

To deal with the greater complexity and extended life durations of new space systems, operations and maintenance concerns must be taken into account during development phases.

Logisticians are being integrated in development teams as well as operations engineers: system design does not only focus on technical performance but also on operations and maintenance because this has a large impact on the costs and on the availability of the space system.

Space projects can be decomposed into three main phases: Development, Assembly Integration and Validation (AIV), and Operations/Maintenance.

The results of the development phase include the spacecraft, the ground control system, and the test equipment. Operations/Maintenance includes mission planning, spacecraft control and monitoring, and maintenance of the ground equipment.

The concurrent engineering trend leads to a more unified view of a space project since the three separate phases are getting transformed into three concurrent activities with a lot of information exchange. This will require harmonised methods, data and tools. MMS is deploying the Intelligent Support to Logistics concept (ISL), based on OPSWARE tools, to support that effort.
For a given spacecraft project, it is quite common to develop many tools and methods that are specific for a given phase even though they seem to be extendible to other problems (see Figure 7).

A common difficulty with this approach is to exchange data across phases and to guarantee the consistency of the data of the various tools.

Of course there are a lot of historical reasons for this partitioning. New technologies, such as OPSWARE tools, should permit a more harmonised approach where the three phases are not completely decoupled. This is the spirit of the ISL concept described in Figure 8.

One direction of work is the harmonisation at the data level, for instance through distributed data bases and/or through the SGML standard. Another direction is the harmonisation at the task level, for instance through OPSWARE tools. These tools have been designed to be easily added on top of conventional information systems in order to improve performances whether or not the information is shared across project phases.

It is clear that harmonisation does not systematically mean uniformisation and centralisation, especially when flexibility is a key concern. For each project one must find a trade-off between the centralised approach and independent tools.

OPSWARE tools call for new types of information sharing, at the task level. This data can be considered as part of the project data base that is getting enriched during the project life time. This is facilitated if all the applications have been designed as a consistent set of tools sharing common concepts. For a given task, e.g. procedure generation, an OPSWARE tool may have to exchange data with sister applications: procedures are derived from various documents and from system data bases, they are manipulated by planning tools and they must be
referenced by diagnosis and data analysis tools. Also, a maintenance planning tool may inherit information from a project planning tool used earlier in the project.

![Diagram of Development, Integration, Operations/Maintenance with OPSWARE, INFORMATION MANAGEMENT, SUPPORT, PROJECT DATA BASE, TO OPERATIONS, PLANNING connections]

Figure 8, MMS Intelligent Support to Logistics concept (ISL).

This harmonised approach is already partly operational at MMS. For instance operations procedures that start being written during spacecraft development, are then shared with AIV and Operations teams.

V. APPLICATION OF ISL TO LARGE SPACE PROJECTS

This chapter describes the parts of the ISL concept that are getting implemented by MMS and explores how other parts of the concept could be fielded.

1. Information Management

A modern space programme generates a large amount of information that mainly consists in documentation of all the parts of the system (ground segment and spacecraft) that is enriched during the various phases, technological data bases (satellite, launcher, payload), and data bases of hardware and software components created for logistics concerns.

These diverse pieces of information must often be accessible in real time by a single user. For instance, a procedure editor must present to an operator, in real time, a part of a technical manual, data from technological data bases (TC profiles, properties of telemetries, synoptics...), properties of equipments. Procedure generation may also require to access mission planning specifications. A system specialist, for instance, may want to browse through the various data and for a given equipment inspect the requirements, ON/OFF command profiles, surveillance telemetries, and skeletal operations procedure.

A common data base in which information is not duplicated provides numerous advantages: concurrency (safe concurrent access to information),
consistency and maintainability. It must be carefully designed to guarantee good performances.

2. Support to Operations and Maintenance

Operations and maintenance activities of ground segments require a strong reactivity from operators and a lot of reliability in decision making and action. This section describes how OPSWARE tools coupled with information management can help meet these requirements.

a/ Prepare and Validate: OPSMAKER

OPSMAKER facilitates the generation of operations procedures of control centers, mission management centers, mission data processing centers as well as maintenance procedures of equipments that constitute the ground segment (antennas, front end equipments, computer systems...). Moreover OPSMAKER should probably be applicable to integration procedures used in spacecraft AIV that have a lot of common aspects with operations procedures.

The procedures can include additional information (text and graphics) extracted from data bases. Debugging and pre-validation of procedures takes place on a workstation that is independent from other ground systems. Formalisation of procedures and modelling of actions facilitate team work by guaranteeing homogeneous procedure manuals. Everybody works at the same level of detail, with the same language. Maintenance of procedures is facilitated since information is never duplicated and powerful search functions are provided. Formalised procedures can also be the basis of training tools to prepare future operators that will use the procedures.

b/ Make Decisions, Execute and Analyse: EOA, DIAMS and X-ANALYST

Formalised procedures can also be used by a procedure execution tool coupled to a control center: procedures are interactively executed in real time and the progress is displayed. That is the main feature of the EOA system.

Monitoring the behaviour of the components during the life time of a spacecraft is a key activity for spacecraft manufacturers. This requires powerful tools that can handle large amounts of data and provide synthetic results (e.g. a parameter is derived from the standard threshold). Intelligent data analysis and report generation are the main features of the X-ANALYST tool. The analysis can also take into account data generated during AIV and data from similar spacecrafts.

Concurrently with long term analysis supported by X-ANALYST, operators must monitor the spacecraft continuously. They must react promptly to an anomaly on a spacecraft, and when they are outside the scope of procedures they must analyse the situation in detail and make decisions. They can be supported by the DIAMS diagnosis expert system which permits to support the operator in the identification of a fault on board the satellite, to capitalise data and experience acquired during the life time of the system, to give access to various pieces of information, and to facilitate operator training.
In short OPSWARE provides two monitoring tools that work in a different time scale: DIAMS is devised for short term monitoring while X-ANALYST focuses on long term monitoring and trend analysis. This monitoring can be implemented on separate computer systems that can even be delocalised from control centers, as soon as telemetry is available. This can facilitate the work of experts who may have availability problems and increase reactivity.

3. Anticipate, Organise and Plan: OPTIMUM

a/ Development and AIV Planning

Stringent constraints on the schedules of space programmes, and the huge amount of activities and events that are involved in the schedules, require powerful, reliable and flexible planning tools. These tools must ease frequent plan revision.

These requirements are met by the OPTIMUM tool that is derived from OPTIMUM-AIV.

b/ Operations and Maintenance Planning

Planning of operations in ground control centers includes:

- mission planning (see for instance PlanERS)
- planning of operations (this is partly covered by EOA)

These plans must be coordinated with maintenance plans:

- planning of preventive maintenance actions
- planning of corrective maintenance actions
- planning of provisioning

Moreover plans must be revised quickly in case of on board problems, mission modifications, software/hardware failures in the ground center.

At each stage, it can be useful to import plans from previous stages and plans from similar projects as a starting point. This is one reason why a unified approach to planning seems particularly interesting.

VI. CONCLUSION

MMS has been developing for several years the OPSWARE concept and the associated generic tools to support space operations. These tools are the basis of several operational applications that have already demonstrated very significant pay-offs for MMS and for MMS customers. This shows once again that AI as a technology must often cooperate with other technologies, like data bases and man machine interfaces, to become effective.
This paper describes how each OPSWARE tool can support logisticians. It also describes how these tools can be integrated in an organised way to form the Intelligent Support to Logistics concept (ILS).

The ILS concept is emerging at MMS, and work with operational teams is on-going to improve the tools and the methods. This task is facilitated by the user’s feedback that has been accumulated over the last couple of years.

REFERENCES


