MEXAR2 : a software tool for MARS EXPRESS data dumping activities

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Abstract

MEXAR2 is an AI system daily in use at the European Space Agency (ESA-ESOC) since February 2005. The tool provides continuous support to human mission planners in synthesizing plans for downlinking on-board memory data from the MARS EXPRESS spacecraft to Earth. Its introduction in the mission planning work flow significantly decreased the time spent in producing high quality dump plans, guaranteeing strong reliability in data dumping and enabling a more intensive on board science activity.

This demonstration aims at showing how the introduction of MEXAR2 has modified the role of the human mission planner, shifting it from computing a feasible dump plan (a time expensive repetitive procedure) to the evaluation and comparison of different dump plans automatically generated and guaranteed feasible (a task that capitalizes the mission planners' expertise).

System Overview

MEXAR2 is the result of a strong effort in the direction of understanding how some expertise from AI P&S (Planning and Scheduling) could have been used to address a real challenging problem in the field of space mission management. Our goal, besides to solving a challenging problem, was to design a usable software to demonstrate the practical applicability of proposed techniques directly into the life-cycle of a real space mission. Both goals have been achieved, since MEXAR2 has been in daily use at the European Space Agency (ESA-ESOC) since February 2005.

The path of the MEXAR2 project starts in 2004, when the authors have had contacts with the Mission Planning Team of MARS EXPRESS, a space mission around Mars (`http://sci.esa.int/marsexpress/`). It clearly emerged that during the first six months of spacecraft activities, the mission planners had faced serious manpower overload in addressing the MARS EXPRESS Memory Dumping Problem (MEX-MDP). The downlink activities were synthesized mostly manually by a team of people continuously dedicated to this task. After three months, authors have been able to deliver to ESA an increasingly accurate operational version of a software able to cope with real problem instances, and real data files. During a subsequent period of three months the tool has been tested back to back against the previous semi-manual procedure developed within the team. Since February 2005 the new operational system

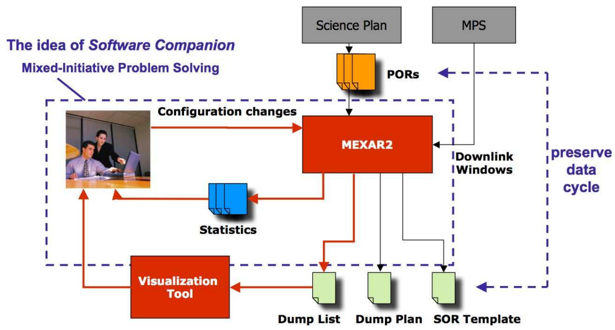

Figure 1: Dump plan synthesis based on MEXAR2

MEXAR2 is in continuous use at ESA-ESOC as the main tool to solve MEX-MDP instances (Cesta *et al.* 2007a). It directly synthesizes commands that implement the data downlink policy from on board memory to Earth. With further work authors have robustified the tool with additional functionalities and a user interface that facilitates its management.

The Problem. MEXAR2 addresses a common problem in space missions, namely data transmission to Earth. In particular the MARS EXPRESS dumping problem (MEX-MDP) arises because a single pointing system is present in the MARS EXPRESS spacecraft. This implies that, during regular operations, the space-probe either points to Mars, to performs payload operations, or points to Earth, to download the produced data. As a consequence, on-board data generally require to be first stored in a Solid State Mass Memory (SSMM) and then transferred to Earth. Therefore, the main problem to be solved consists in synthesizing sequences of spacecraft operations (*dump plans*) necessary to deliver the content of the on-board memory during the available downlink windows. This allows to save upcoming pieces of information without losing previously stored data and to optimize given objective functions (see (Oddi *et al.* 2005) for a more accurate description of the dumping problem).

Integration with ESA ground segments. The current procedure for synthesizing dump plans with MEXAR2 in the loop is shown in Fig. 1. MEXAR2 directly accepts as input the POR requests from the science plan (Payload Operation Request files contain the storage operations that on-board instruments are supposed to generate), and the speci-

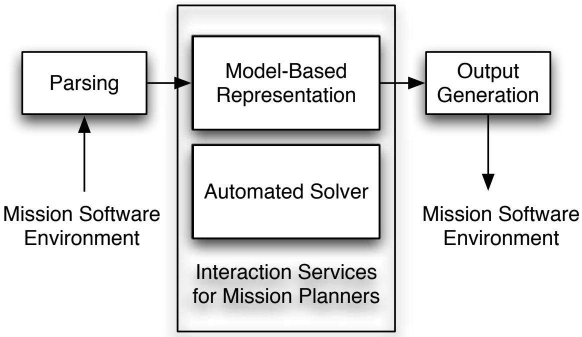

Figure 2: The general architecture underlying the approach

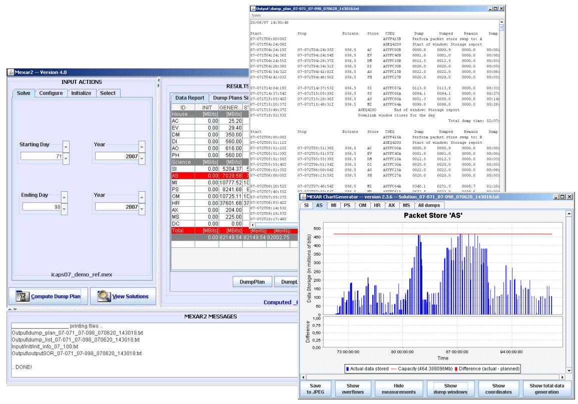

Figure 3: MEXAR2 Interaction Modules

fication of the downlink windows from MPS (Mission Planning System). It produces as output the dump plan in the three formats expected by ESA people (DumpList, DumpPlan and SORtemplate in the figure). This has been obtained by encapsulating the intelligent system between two software modules (see Fig. 2): a first one (the *Parsing* module) responsible for processing the input files and selecting the relevant information for the symbolic model used by the solver, and a second one (the *Output Generation* module) for manipulating the results produced by the system and generating the output according to external formats.

Generic software architecture. Apart the connection with the mission software cycle, Figure 2 shows also a sketchy blow up of MEXAR2 components. The core part of the system involves three modules: (a) a domain modeling part (Model Based Representation in the figure), (b) an algorithmic module (Automated Solver), (c) an interaction module (Interaction Services) that allows mission planners to access both previous modules. The two further modules for pre- and post-processing to connect to standard software cycle directly interact with the model based representation that act as the core module of the whole approach.

Using MEXAR2

We have designed a highly interactive tool that enhances the capability of the users offering a change of perspective in generating a solution. Users do not directly iterate in the attempt of "almost manually" producing the dump plan, as was done before MEXAR2, they rather establish a dialogue with MEXAR2, having access to the model of the domain and dials to tune the algorithms. From MEXAR2 they receive also additional information, for short referred to as Statistics in Fig. 1. This information enrich their ability to analyze the current solution. In general we have pursued the goal of allowing users to take more strategic decisions, and maintain control over the synthesis of *dump plans*, delegating to MEXAR2 not only the repetitive part of the work but also the proactive role of creating the dump plan. This has been achieved by exploiting MEXAR2 ability to work quickly and to consider clues given by solving strategies. In other term all the parts of the intelligent system have been designed to allow a mixed-initiative problem solving activity. Being relieved from the tedious and difficult part of the task, the mission planners can now concentrate on strategic decisions. MEXAR2 can be in fact iteratively configured to reproduce changes in the domain or to tune the parameters of the solving algorithms. In particular it is possible to create alternative configurations of the tool which correspond to diverse situations of the real world (e.g., different level of residual data, extra dumps based on incidental events, changes in priority of data to be downloaded, etc.) and quickly obtain the corresponding solutions from the tool.

A further valuable help of the mixed-initiative style is the possibility to jointly build, save and evaluate several solutions with the aim of avoiding potential data loss and more in general to look for more optimal results. Indeed, by using MEXAR2 as an active collaborator, overwrites can be quickly detected during the medium term planning process and fed back to the science community for POR update (i.e., to correct the case of anticipated data loss).

The interaction between MEXAR2 and the user is friendly and based both on textual and graphical input/output (see Fig. 3). The input is provided to the system through some panels that drive the user, while the output is produced both on ESA tabular format (the output files) and on user-friendly graphical presentation of interesting measures.

Input Actions. The basic action consists in the specification of the dump interval, the starting and ending dumping days.Then, through three sub-panels, users communicate to MEXAR2 additional information. In particular (a) the "*configure*" action allows to specify the domain model, e.g., the specification of packet stores, their size, their respective priorities, their need to be robustified, etc.; (b) the "*initialize*" action communicates to MEXAR2 the residual memory stores from the previous temporal interval that are to be downloaded together with data related to new PORs; (c) "*selecting*" through this pane users can tune the parameters of the algorithms.

Automated solution. Once the needed context and the required parameters have been specified, users may ask the solver to compute a dump plan by clicking the "Compute Dump Plan" button. Feedback about the solver decisions is provided through the MEXAR2 Messages pane. MEXAR2 provides different solving algorithms. A basic solving procedure looks for solutions without considering the packet stores priorities. A second one, takes into account the priorities, while a third algorithm aims at obtaining robust solutions. The pursued idea of robustness is the one of avoiding that a single memory bank is extremely full of data so that any variation at run time is difficult to be absorbed with consequent high risk of overwriting. An additional aspect that the algorithms have addressed concerns the "fragmentation" of the whole dump plan. In this respect the user can specify different thresholds, called input and output thresholds, that avoid production of commands too short or that dump too little data.

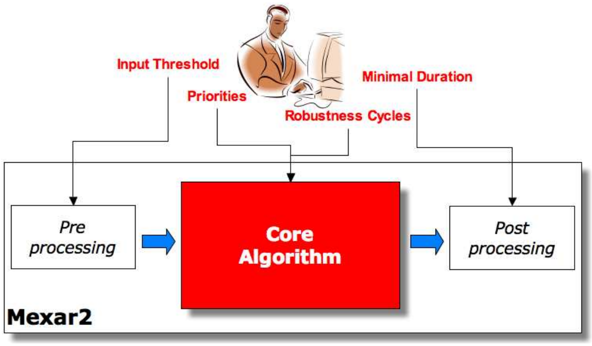

Figure 4: Sketch of the solver

Inspection of Results. Once the solver has found a solution, the Interaction Module shows the results. A set of statistics are shown in the "Results and Statistics" pane that provides aggregate information on the current solution. In particular a panel named "Data Report" is shown, with entries subdivided into packet stores. This report gives the user an immediate view of the input/output data balance. Apart the Data Report table, the basic pane allows to access the three main files that are produced by the solver through three buttons ("Dump Plan", "Dump List", "Output SOR"). ESA provided us a Visualization tool, developed in-house to validate results of MEXAR2, see Fig. 1, that has been inserted as an additional plug-in.

Computing different solutions. As said before we have worked to endow the system with functionalities that support the user in exploring different solutions. The mission planner can indeed generate different *use profiles* of the tools acting on the "configure" and "select" features and compare various results. To facilitate this activity we have also introduced an additional structure called *Solution Data Base* that, for any time interval, shows a table with all the solutions computed for the period. For each solution in the table, users can see the settings used to obtain it and a summarization of different metrics for evaluation.

The solving algorithm of MEXAR2 is organized as sketched in Fig. 4: an effective core algorithm computes complete solutions on a given problem; a set of heuristic *modifiers* are used to influence the core algorithm in order to obtain different solutions according to specific qualities measures. For this demonstration we dedicate attention to the modifiers, while see (Cesta *et al.* 2007b) for further details about solving related aspects.

In general, while a solution should satisfy all the imposed constraints, the modifiers influences the quality of the solution. In fact MEXAR2 can find *high quality* solutions with respect to some metrics.

Metrics. In particular, we follow four quality metrics: the percentage of data *lost*, the *size* of a dump plan, the *robustness*, and the *weighted delivery delay*. For all the metrics, *the lower the value, the better the solution*. A short justification for each metric is given below.

Data Lost (LOST) – Percentage of the *total input data* lost over the planning horizon. Total input data represents the sum of the initial volumes of data in the packet stores and the volumes of data produced by all the considered store operations.

Plan Size (SIZE) – The number of dump commands in a solution. This is an important quality of the plan because each command requires both a certain time to be uplinked to the spacecraft and a memory space on-board before being executed. For these reasons mission planners strongly prefer short plans. Being able to control this quality metric is an important ability of MEXAR2.

Robustness (RBT) – In the case of the MEX-MDP problem our aim is to control the level of memory use in order to avoid possible loss of data due to overwriting. One possibility for overwriting can occur when a greater than expected volume of data has to be stored and there is not enough space in the packet store. For this reason we define a *robust* solution a solution in which a specified amount of space of each packet store is preserved in order to safeguard against overwriting (see (Oddi & Policella 2007) for further details). The robustness of a solution is defined as the maximum value of packet store utilization (specified as a percentage of its total capacity).

Weighted Average Delivery Delay (WDD) – given the set of store activities, it is the average of the times elapsed from the instant when a generic store activity memorizes the carried data in the on-board memory and its delivery time. This value is weighted by the packet store priority, such that the higher the priority, the higher WDD.

Informally we can state that *a high quality plan delivers all the stored data (no overwriting is allowed), contains the smallest number of dump activities, satisfies the priorities preferences imposed on the set of packet stores and is able to "absorb" external modifications that might arise in a dynamic execution environment.*

Heuristic modifiers. Being a key issue the flexibility of the solver with respect to the users that maintain responsibility of the plan choices, a lot of work has been dedicated to make the solver usable for solution space exploration by acting on the "modifiers knobs". The setting of the four parameters represents the *core* actions for driving the search towards solutions with different quality metrics. As sketched in Fig. 4 the heuristic modifiers to explore the solution space are the following.

Input threshold – Each scientific observation, the POR, produces a sequence of data records which represent the input store operations for the solving algorithms. A threshold value can be set for each packet store and represents a given percentage of its overall capacity. By setting a threshold, a sequence of many small data records targeted on the same packet store are grouped into a single cumulative record and stored at the end of the grouped sequence. So, many small data records are grouped into a single one and tends to be dumped by a single command.

Priorities – The priority values of the packet stores. The allocation of dump commands can be done considering the priority values of the packet stores.

Robustness Cycles – As we have seen the robustness copes with the uncertainty on the exact amount of produced data. We have defined as robust a solution in which a specified amount of space of each packet store is preserved in order to safeguard against overwriting. The algorithm can iterate to achieve robustness.

Minimal Duration – The minimum allowed duration for a dump command is another parameter of a certain interest. In order to met this last requirement, the output solution is post-processed in order to remove possible short commands. This parameter complements the threshold acting as a post-processing while (see arrows in Fig. 4) threshold acts as a preprocessing with respect to the core algorithm.

Demonstration

The MEXAR2 demo aims at showing how the performance of the system can be driven toward an high quality solution by tuning some interaction parameters.

We perform the demonstration of the system on a benchmark set which refers to an interval of 28 mission days covering last March and April 2007, in particular, within the period *[071 07, 098 07]* (*[start-day year, end-day year]*). This is really a critical benchmark and is a probable candidate for loosing data during the execution of the related dump plan. For the sake of completeness, the used benchmark has a total number of stores equal to 4064 and the total number of PORs is 358.

Within this interval of time we perform a three step demonstration, to point out the three major features of the system: (1) the solution of a problem, (2) the solution repository management and the tuning of the solving parameters and (3) the symbolic domain editing.

First Round: Solution of a reference problem. This step aims at showing the basic functionalities of the system. For this purpose MEXAR2 runs over an input reference problem with the following basic sets: no threshold for input storage commands, no robustify cycles and no minimum allowed duration for dump commands. During this step the demonstrator shows both input files ingested and output files produced by the system (both of them are original ESA formats): this points out that preserving existing data lifecycle has been a principal issue in designing MEXAR2. Finally the demonstrator shows the features for inspecting the solution: different views of packet stores usage, download windows occupation and data management (tables and charts).

Second Round: Solution repository and modifiers. This step aims at showing how mission planning crew uses the system as a support to develop a long term strategy for data dumping. MEXAR2 allows the management of a repository of solutions. The demonstrator first shows the repository management functions, then populates the repository with different solutions. These solutions are computed for the same interval of time as the reference solution, but threshold parameters, robustify cycles and minimal dumping command duration are tuned. Finally a solution of the reference problem is computed with a potential operative setting (settings tuned by ESA people in the operational environment). The choices of the setting for the various solutions have been tuned to demonstrate the influence of those parameters on different qualities of the solution. The main goal of this step is to demonstrate how the issue of maintaining mission planner control and responsibility during problem solving has been taken in account in designing MEXAR2.

Third Round: Symbolic Domain Definition. The last step concerns the MEXAR2 symbolic domain management. Since MEXAR2 is an AI based system, the model of the spacecraft and of the MEX-MDP is a symbolic description of a set of resources (the packet stores) with their properties and a set of constraints over the commands of dumping plans (like temporal constraints about the separation of the commands in the plan). The demonstrator shows a MEXAR2 domain, explaining the symbolic model. Then it modifies some parameters and constraints, showing how the high level symbolic model (designed to be close to the usual terminology of ESA ground segment staff) drives the generation of the dump plan.

Acknowledgements. The European Space Agency has sponsored this work under contract 18893/05/D/HK(SC).

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