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User Interaction with an Automated Solver
The Case of a Mission Planner

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ABSTRACT

An effective interaction with the user is a key aspect for the success of technological tools applied to both everyday and highly specialized tasks. This paper shows features of MEXAR, an intelligent system that solves a mission planning problem related to the MARS EXPRESS program of the European Space Agency. The paper describes the MEXAR interaction module developed to support human mission planners in a specific daily task, which consists in generating commands for downloading the on-board memory of the spacecraft. The interactive environment of MEXAR helps a user to analyze the current problem and takes planning decisions as a result of an interactive process enhanced by various elaborate facilities. Different interactive techniques have been integrated to address two different aspects: (a) developing trust on behalf of the user in the automated algorithms; (b) promoting a deep participation of the user during problem solving. An integral part of the tool development process has been a usability study on MEXAR'S Interaction Module, aimed at discovering possible problems in user-system interaction. This paper discusses how the enhancement of both transparency and usability of automated decision making tools is fundamental for users' acceptance of artificial support systems and their profitable deployment in real world applications.

Keywords: *human-computer interaction, interactive problem solving, planning and scheduling problems, user involvement, space applications.*

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1. Introduction

State of the art interactive technology could be very useful in supporting human tasks, and its application may vary from simple systems able to support daily human activities, to more complex and sophisticated decision support tools (e.g., in the context of medical environment, transportation domain, space missions) that help human decision makers in taking important and difficult decisions. Unfortunately, very often,

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the automated tools present deficiencies and shortcomings resulting in a non effective usage or in the user not to trust them. There are at least a couple of reasons for this mistrust of the automated systems. Most of interactive devices are endowed with a "bad designed" interface, which does not present information properly so to satisfy the user's needs. A user tends to be skeptical toward the use of a *black box* that hardly explains choices, actions and results. An appropriate and effective representation of problem modelling, all objects and entities involved and the solutions or the advices proposed by the artificial aid are to be guaranteed, in order to promote a more fluid and flexible interaction.

The naturally conservative behaviour of people in changing their habits makes it difficult the spread of such a supporting technology, in particular in those contexts in which critical decisions are to be taken. The final user of systems of this kind is used to make decisive choices and perform complex tasks completely "by hand" and the attempt to *automate decisions* or *jobs* it is not a trivial problem. Users tend not to abandon their traditional way of working and get into new habits, unless, we believe, this entails higher quality, higher speed in obtaining outcomes, more stimuli, less annoyance, certainty of the correctness of the results and above all the possibility to actively participate being in charge of the final decisions.

For these reasons the design of interactive systems is a hard and challenging problem and the success of their use is also dependent on an effective and useful *interaction module*. It is worth noting though that most of the automated systems belonging to the past generation, failed in their attempt to support users' tasks or problem solving due to a common lack of attention to the user. We are referring to a usual attitude of focusing on the development of powerful and efficient algorithms to automate tasks, while ignoring the important issue of making systems usable and interactive. Most of the automated systems do not support users properly because they are lacking an effective interaction module that keeps the user in the loop. The interaction environment should guarantee a friendly and comprehensible representation of the problem, the problem solving process and the solutions, especially in those cases in which the automated system is devoted to support a user in solving complex problems. It should allow a user to verify the correctness of the results, the possibility to express her/his own preferences, and a continuum in changing her/his way of working, by allowing a gradual adaptation to the innovation. The interaction module bridges the gap between users and artificial solver hiding useless details and technical complexity. It should promote a stimulating and effective work environment to enhance human problem solving capabilities.

In this paper we present our experience in developing a tool for supporting the user in the context of a space mission. We report on work done to design and realize an intelligent system able to represent in a compact and meaningful way a huge amount of complex information and solve an involved problem. The context of our study is MARS EXPRESS, a space probe launched by the European Space Agency (ESA) on June 2, 2003 that has been orbiting around Mars since the beginning of 2004 for two years.

The paper briefly describes the addressed problem and the problem solving, then mainly focuses on the description of the interactive techniques designed and implemented within an integrated system, named MEXAR.

The paper is organized as follows: Section 2 describes the MARS EXPRESS mission and briefly introduces the addressed sub-problem (MEX-MDP problem); Section 3 shows the software architecture designed to solve the examined problem; in Section 4 the main ideas to design interactive services supporting human planners are introduced, together with a description of their implementation within MEXAR; Section 5 shows how usability techniques have been applied in MEXAR interface. Section 6 discusses some related work, while some conclusions on our experience end the paper.

2. A study in the context of the space mission MARS EXPRESS

An orbiting spacecraft continuously produces a large amount of data which derives from the activities of its scientific instruments (payloads) and from on-board device monitoring and verification tasks (the so called *housekeeping data* analyzed to check the safety of the spacecraft). All this data, usually referred to as *telemetry*, is to be transferred to Earth during downlink connections. MARS EXPRESS is endowed with a single pointing system, thus during regular operations, it will either point to Mars and perform payload operations (scientific observations) or point to Earth and transmit data through the downlink channel. As a consequence on-board data is first stored on the on-board memory then transferred to Earth during *temporal visibility windows*. MARS EXPRESS contains seven different scientific payloads which will gather different data on both surface and atmosphere of the Red Planet. During the operational phase around Mars a team of people, the Mission Planners, are responsible for deciding the on board operations of MARS EXPRESS. Any single operation of a payload, named POR for Payload Operation Request, is decided well in advance through a negotiation phase among the different actors involved in the process (e.g., scientists, mission planners, flight dynamics experts). This negotiation causes (a) acceptance or rejection of a single POR, (b) assignment of a start time to the accepted PORs. The mission planners' goal consists of guaranteeing an acceptable *turn-over time* [3] from the end of the execution of the POR to the availability on Earth of data generated by that POR.

An effective management of on-board memory and a good policy for *downlinking* [4] its data are very important for a successful operation of the spacecraft. The authors' study has addressed the problem of automatically generating downlink commands for on-board memory dumping. They have formalized the problem as the MEX-MDP (MARS EXPRESS Memory Dumping Problem), defined a set of algorithms to solve the problem, and implemented an interactive system, named MEXAR, which allows human planners to continuously model new MEX-MDP instances, solve them, inspect a number of problem and solution's features. The reminder of this section briefly reports the solved problem while a more detailed description is given in (Cesta et al., 2002).

Fig. 1: The mission of MARS EXPRESS is to orbit Mars and provide scientists with high definition images and spectra. An artist's impression of MARS EXPRESS in orbit around Mars is provided on the left, while the picture of the right shows one the first images of the Martian surface taken by MARS EXPRESS – Both pictures are courtesy of ESA.

The basic ontological objects that describe the MEX-MDP problem are *resources* or *activities*. *Resources* represent domain subsystems able to give services (e.g. photo-cameras, on-board memory); *activities* model tasks to be executed (e.g., take picture)

[3] With *turn-over time* we indicate the temporal delay between the end of a scientific observation and the instant in which the related data produced by the observation is completely transmitted to Earth.
[4] The term *downlinking* will be used in the paper to indicate the activity of data transmission from the satellite on-board memory to the ground station on Earth.

using resources over time. A set of *constraints* defines needed relationships between the two types of objects (e.g., the on-board memory has a limited capacity).

The relevant types of resources in MEX-MDP are the set of packet stores, the set of on-board payloads and the set of communication channels:

- *Packet Stores.* The on-board memory (Solid State Mass Memory) is subdivided into a set of independent packet stores that cannot exchange data. Each one has fixed capacity and an associated priority value reflecting the importance of the stored data. Data produced by scientific observations is organized in data packets and then stored in the assigned packet store.
- *On-Board Payloads.* An on-board payload represents a scientific instrument used to perform observations. Data produced by scientific observations is organized in data packets and then stored in the assigned packet store.
- *Communication Channels.* These resources are characterized by a set of separated communication windows identifying intervals of time for downlink (*temporal visibility windows*).

The amount of each resource is constant and known in advance.

Activities describe *how* resources can be used. Two types are relevant in MEX-MDP: payload operations and memory dumps. Each type of activity is characterized by a particular set of resource requirements and constraints.

- *Payload Operations.* A payload operation request (POR) corresponds to a scientific observation. Each observation generates an amount of data that, according to the MARS EXPRESS operational modalities, is decomposed into different *store* operations, and distributed over the set of available packet stores. Payload Operations represent the *input* for the system.

- *Memory Dumps.* A memory dump operation transfers a set of data from a packet store to a transfer device. These activities represent data transmission through the communication channel. Memory Dumps represent the *output* of the system.

Given a set of POR operations, a *solution* to a MEX-MDP problem is a set of Memory Dumps that satisfy all the constraints imposed by the system (finite capacity of the packet store, visibility windows, etc.). An additional goal is to find *high quality solutions* with respect to a set of evaluation parameters; usually high quality solutions deliver all the stored according to a definite policy or objective function (e.g., data delivery time to Earth).

3. An intelligent software for scheduling data return

In order to solve MEX-MDP problems we designed the MEXAR architecture which uses Artificial Intelligence (AI) techniques to model and solve the problem. In particular our system combines Planning and Scheduling (P&S) technology with flexible interaction modalities in an overall interactive tool. It is worth noting that P&S technology is mainly devoted to *automate decisions* while common practice in space missions is that *decisions are taken by humans* and only low level activities are automated. The traditional management of the data return problem is an example of a mostly "hand made" activity where the human mission planner works at a very low level of abstraction, consulting different support tools only for specific computation. Moreover, as already said in the introduction, users tend to be skeptical toward novelty and changes in their way of work, especially in those contexts where difficult decisions are to be taken that may cause undesired failures. For these reasons we decided to use a conservative approach to the problem, and designed a decision support aid that benefits from the computational strength of the automated algorithm but leaves the humans in charge of their responsibilities. The general framework of the system is composed of two modules as it is shown in Figure 2.

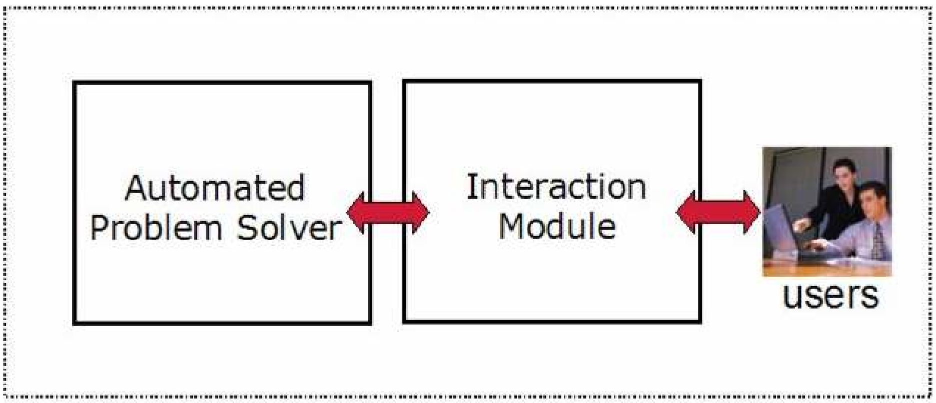

Fig. 2: Generic architecture for an interactive intelligent system

The first module, named *Automated Problem Solver*, models the real domain, and captures the dynamic rules according to which the domain evolves. This module relies on an internal representation of the problem which is suitable for both automated algorithms and interaction with the users. The internal representation models relevant knowledge as a set of constraints and provides data structures for representing the domain, the problem, the solution and its management. On top of this representation a set of automatic algorithms guide the search and generate problem solutions. The second component of the system is the *Interaction Module* that directly interacts with the user, and allows her/him to take part in the process of finding a solution by providing advanced interactive facilities. It represents the communication channel between the user and the automated solver and a means to exploit powerful features of the automated system. Aspects of the two modules are described in the rest of the paper.

3.1 Problem Solving in MEXAR

Our approach to solve MEX-MDPs is grounded on the Constraint Satisfaction Problem (CSP) paradigm (Tsang, 1993). This problem consists of a set of variables $\{v_1,v_2,\ldots,v_n\}$, each with its own domain of values $\{D_1,D_2,\ldots,D_n\}$, and a set of constraints $\{c_1,c_2,\ldots,c_m\}$, that define the relations among those possible values. A solution *s*, consists in assigning to each variable one of its possible values, $v_i = d_i$ with d_i belonging to D_i, such that all the constraints are satisfied.

A MEX-MDP instance has been represented as a Constraint Optimization Problem (COP), the optimization version of a CSP. In this case the assignment that optimizes a defined objective function *f(s)*, is selected. In our case the objective function concerns the temporal delay between the end of a scientific observation and the instant in which all the related data is completely downlinked to the ground (*turn-over time*). For further details, we defer the reader to (Oddi et al., 2003) where a thorough discussion for both MEX-MDP representation and the automated algorithms is provided. In this context we highlight our attempt to develop a support tool that helps the human mission planner by providing advanced problem solving facilities, without changing radically her/his traditional work modality.

On top of the constraint based representation for MEX-MDP, a multi-strategy solving method with a portfolio of algorithms has been developed. The idea is to endow the human mission planner with a set of solving algorithms she/he can choose among, in order to automatically get a solution to the problem. In particular MEXAR provides two solving algorithms, a greedy solver and a random sampler, and an optimization procedure based on tabu-search to iteratively improve solutions (Oddi et al., 2003). In this light the problem solving process can be seen as a two step procedure: first, an initial solution is found by using either the greedy algorithm or the random sampler. Once an initial solution is obtained, it is possible to look for improvements by using an optimization strategy. The optimization method explores the solution space according to different principles trying to achieve a solution with a better value of the objective function. A “friendly” graphic interface abstracts the complexity of the problem representation and the technicality of the solving algorithms and provides a high level description the algorithms' features. Through this representation a user can easily choose and configure the solving algorithm by tuning the requested parameters according to her/his preferences. In this way she/he maintains a level of control on the solving process.

4. The user interaction with MEXAR

MEXAR is endowed with a sophisticated interaction module that allows a user to easily supervise and control the entities of the domain and the whole solving process, being aware of all the steps the solver goes through. Specialized interactive functionalities provide a user with satisfactory information services and control facilities. They put at user's disposal the possibility to inspect the problem and obtain an initial solution by choosing among different solving algorithms she/he can personalize. Moreover an advanced environment allows an expert user to select the best solution for the execution as result of a “step by step” procedure enhanced by incremental improvement algorithms, evaluation services, and graphic comparison functionalities.

4.1 Designing interactive functionalities

Before describing the interaction functionalities MEXAR is endowed with, we shortly introduce two main problems that have been taken into account while developing the Interaction Module. In our opinion, such problems need to be constantly addressed in the design of interactive systems.

- **Visualization problems.** It is the need to guarantee a certain level of “transparency” to the user, providing comprehensible and significant representations of the real domain, the problem, its solutions and the problem solving process. These needs are also related to the mentioned general skeptical attitude of the users toward automated systems. In order to gain user's trust an automated system should be endowed with clear and expressive representation services. We refer to this as to the *glass box* principle, contrasting the widespread trend, among the users, to consider the automated systems as a *black box* to be distrustful or suspicious of.

– **Interactive user participation.** The idea is to capture different skills that a user and an automated system can apply to the resolution process. Typically an algorithm can perform better on conducting repetitive search steps that are not possible for a human user, while the user usually has more specific knowledge on a domain that is often difficult to formalize in terms useable by an algorithm. The overall systems Human Planner/Artificial Solver could be considered as more powerful and able to more efficiently solve a problem. The Interaction Module plays a crucial role in enabling such cooperation and should provide interactive services and functionalities to promote a combined problem solving.

In the following we provide a description of how these ideas have been implemented within the system in the attempt of addressing the two main issues discussed above.

4.2 Implementation of the functionalities

While designing an Interaction Module for MEXAR we have been thinking of how to solve the problem of visualizing a huge amount of complex information, providing a user with an environment that enables to express her/his preferences and actively participate in the problem solving.

Visualization problem

The CSP approach underlying the automated solver uses a symbolic model of the domain features subdivided between activities and resources. Based on a *glass box* principle, the MEXAR interface provides a meaningful visual representation for all the entities relevant in this domain model.

A specific dialogue allows choosing one of the problems to be solved and to instantiate its CSP representation. Such representation is used to display information of the interaction panel. Figure 3 presents the basic layout of the MEXAR interface. In particular it shows the basic visualization of a MEX-MDP problem.

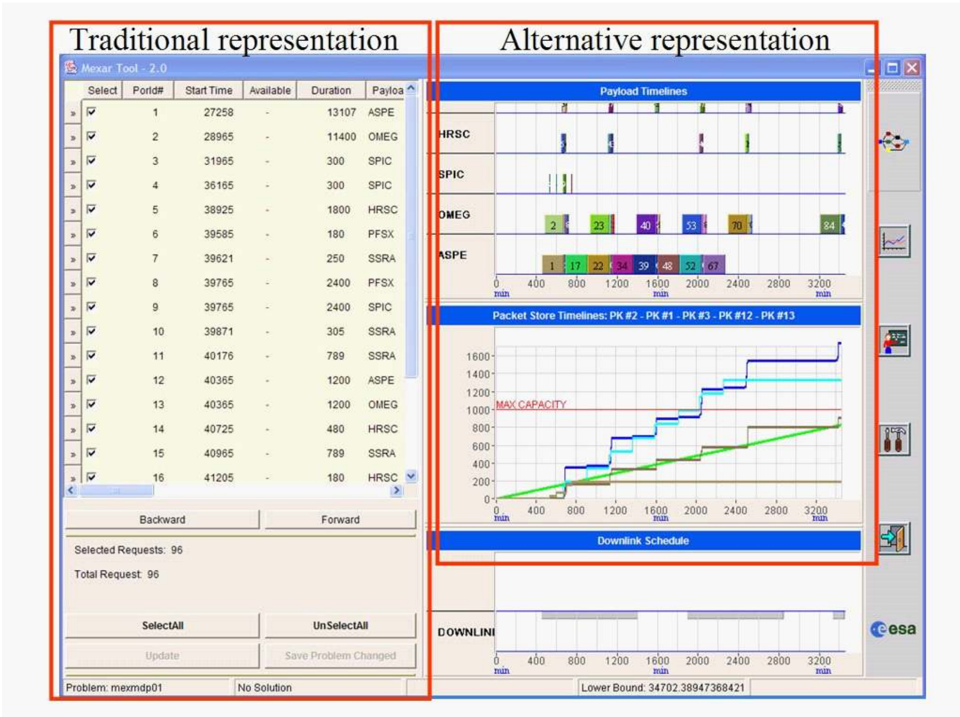

Fig.3: Visualization in MEXAR: examining problem features

The left panel in the layout shows the list of Payload Operation Requests (PORs) in textual form, that is a detailed list of information on the input activities, their temporal allocation, and the distribution of their data on different packet stores. Then three different panels on the right part of the layout (one on top of the other) represent the timelines (distribution over time axis) of the different domain features relevant for the user. The first panel (higher panel on the right) shows the Gantt Chart of PORs in the problem. This is a graphic representation of the input activities of the problem over time. For each payload there is a different timeline where each POR is represented by a coloured rectangle labelled with a natural number (PorId#) starting from its start time.

A graphic representation of the temporal function representing the volume of data stored over time is given in the central panel on the right. A line labelled “MAX CAPACITY” indicates the packet store capacity. As the reader can notice, data in the packet stores in Figure 3 will exceed the max capacity which entails that downlinking is necessary to avoid overwriting[5].

The last panel on the right will contain the memory dump activities (solution), after the solver activity (see Figure 4).

[5] Each packet store is managed cyclically. When a packet store is full, any new information overwrites the older one.

These three panels form the basic information the user should be familiar with in order to develop trust in what the solver is representing and managing. A major software development effort has been needed by those three panels that, for example, should be constantly synchronized in their scrolling to represent a consistent model of the world. This temporal representation of the internal symbolic model used by the CSP solver has been instrumental for convincing the ESA personnel that the solver was addressing exactly the problem they had.

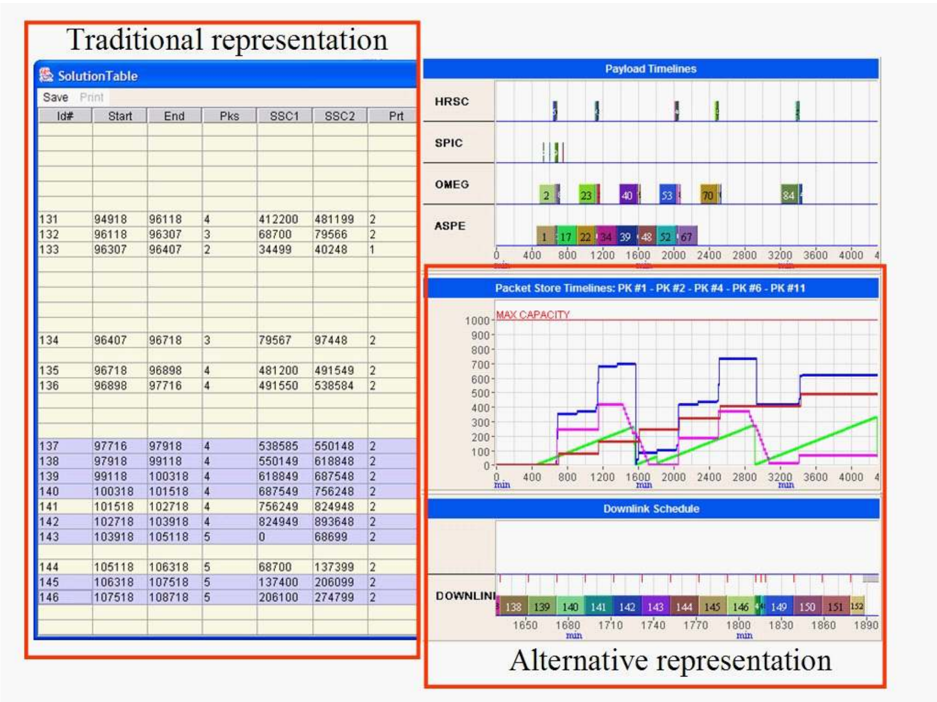

Fig. 4: Visualization in MEXAR: studying a solution

In Figure 4 a solution for the problem is shown. In the left part of the panel a textual representation of the solution is given, while an alternative graphic representation is shown in the third panel on the right.

Before solution (see Figure 3), the user can see static features of the problem, and inspect any of its aspects in detail. After solution, the user can immediately understand if a solution has been found, and have a visual view of the load on each packet store (see the difference between before and after on the center right panel). In the example of Figure 4 the maximum capacity constraint is never violated due to the effect of different dumps (the packet stores profile is always below max capacity). The sequence of dumps on the communication channel (lower right panel) completes the information on the solution. In this last panel a bar represents the time intervals where it is possible to perform memory dumps (visibility windows). Intervals where dumping is not possible are drawn in grey.

In providing different and alternative representations within MEXAR we paid attention to design an interaction modality quite close to the traditional way of working of the human planner. In this way a user can count on a system that facilitates her/his task by providing information and solutions close to the way she/he is used to, and get gradually acquainted with the alternative interaction modalities. The "traditional representation" of the problem and the solutions provides a detailed description very close to the one the human mission planner is used to. We are referring to the PORs list in textual form, specifying in detail the related information (Figure 3) and to the solution table that reconstructs all the details concerning the solution of the current problem (Figure 4). The alternative graphic view represents a more compact, intuitive and high level vision of the problem and the solution. It is worth saying that the solution table reflects the current way of working at ESA, in fact mission planners mainly deal with numerical data contained in spreadsheet tables. Using the table it is possible to check for example (a) how the data from a single POR is segmented in different dump operations, (b) how the time of data return has been generated, etc. In general, it could be also possible to directly generate the dump commands from the lines of the table. In fact, the whole table can be saved as a separate file and manipulated by different programs.

A user is free to use only one or both modalities. The two representations are indeed linked and synchronized to each other through a set of interactive links. For example, the alternative representations for the PORs (the one on the table and the one on the timelines) are not redundant as they focus on different aspects. In fact, the list of PORs on the left gives detailed information on the payload activity, while the Gantt on the right focuses on their temporal allocation, and allows to have a feeling of the impact of any POR on the packet stores *via* the other synchronized right panels.

Another feature of the module is the possibility to evaluate a solution according to some metrics. This possibility enables the user to easily estimate the quality of a solution with respect to some chosen parameters. In fact, a graphic evaluation has been added to obtain an immediate level of evaluation of the current solution.

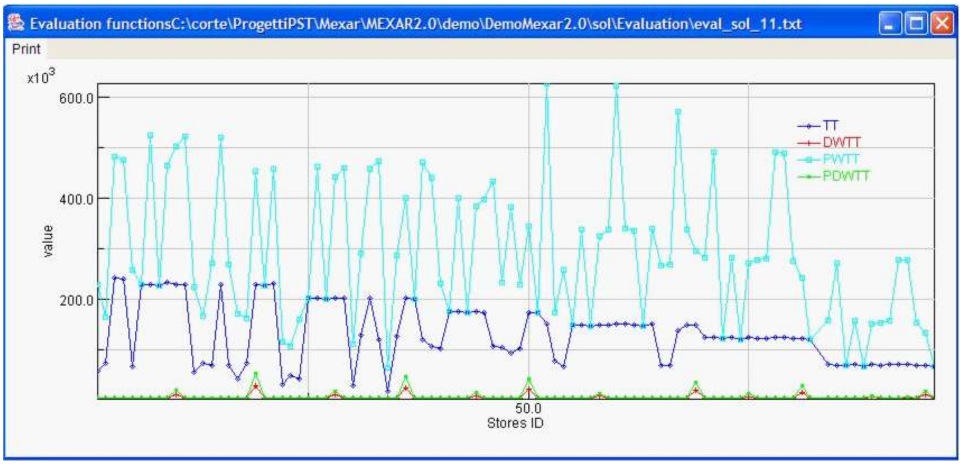

Fig. 5: Evaluating a solution.

When calling the command from the menu a new dialogue window allows choosing one or more evaluation functions. Figure 5 shows an example, where the x axis represents the PORs, while the y axis represents the turn-over time.

A number of other small interaction features are implemented as basic functionalities but are not described here because they do not change the general perception of the interaction flow.

User participation in problem solving

Once the human planner has deeper knowledge of the problem and all the aspects it involves, she/he can start a different level of interaction with the system trying to contribute with her/his expertise and judgment to the problem solving activity. In this way she/he can possibly choose either to completely entrust the system with the task of finding a solution or to participate more interactively in the problem solving process.

MEXAR puts at her/his disposal a second interaction layout, called Solution Explorer that is intended as an example of such an enhanced interaction environment. This second layout has been created mostly for showing ESA personnel an example of advanced functionality based on our interactive problem solving technology. As said before the Automated Solver allows a user to apply different solving methods to the same problem. Specific functionalities enable the user to save different solutions for the same problem and to guide a search for improvements of the current best result by applying different optimization algorithms. The idea behind this aspect of MEXAR is to deeply involve the expert user in the problem solving process. A user might generate an initial solution, save it, try to improve it by local search, save the results, try to improve it by local search with different tuning parameters and so on.

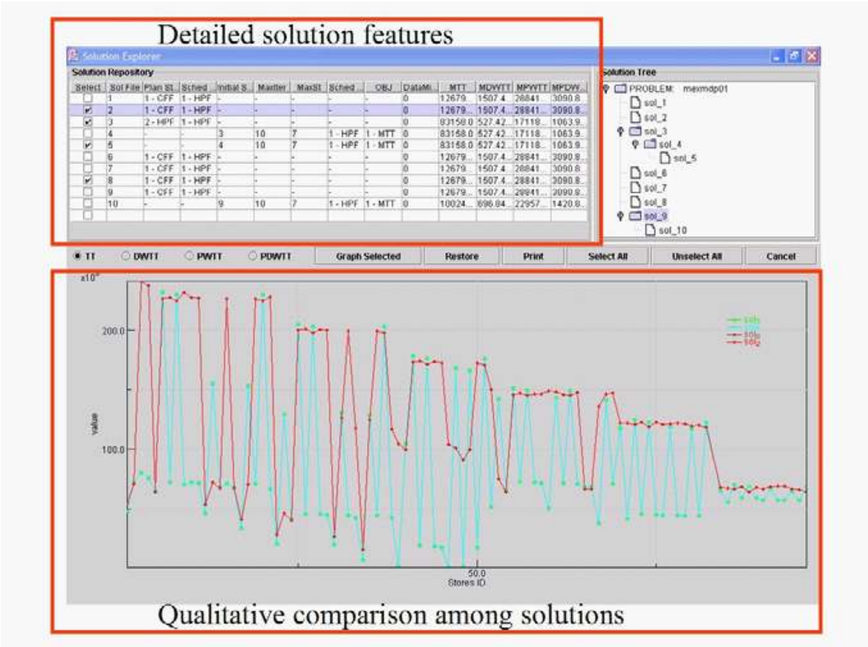

Fig. 6: Involving the user in the problems solving process. A step in exploring the solutions space.

This procedure can be repeated for different starting points, resulting in the generation of different paths in the search space. Using both the evaluation capability on a single solution and her/his own experience the user can visit the different solution series, all of them saved, and, at the end, choose the best candidate for execution. Figures 6 and 7 show two examples of use of the interaction environment, in particular depicting a single problem at different stages of exploration. Studying the examples, it is possible to see that our idea has been again that of facilitating the analysis of the current problem by providing multiple representations of the solutions features. A user has different tools to evaluate the solutions and can either generate new ones or choose the best one according to different temporary criteria.

The ideas behind the iterative construction of a solution in MEXAR provides a concept of human guided search (see also different approaches like (Anderson et al., 2000)), that can be very useful in the search for a solution to complex problems. Indeed, in the current version, the Solution Explorer provides an inspectable repository.

After selecting a solution from the tree, the user can inspect various quality measures. Attention has been devoted to building an interface that allows the user to be in control on the different solution paths without getting lost in the increasing number of solutions. This environment can become increasingly useful if the user were endowed with more complex and powerful means to influence the artificial solver.

Fig. 7: Involving the user in the problems solving process. A more advanced state in the exploration.

Somehow, our desiderata would be to continue the development of the system in this direction, which is not part of the initial study, in order to obtain a more advanced example of mixed-initiative interaction (Burstein & Mc-Dermott, 1996; Cohen et al., 1999). This term generically identify the problem of creating solving environments in which users and automated systems cooperate in problem solving contributing with their respective abilities. Nevertheless the Solution Explorer represents a proof of concept which is very useful for tuning future directions.

5. Evaluation

MEXAR has been delivered to ESA-ESOC in May 2002 and is currently available to the mission planners. Users' reactions to the system have been quite positive. We highlight in particular a real interest in the idea of using an automated tool that performs boring and repetitive tasks on users behalf, while preserving humans control on the flow of actions and the possibility to choose the final solution supported by the automated tool.

Interactive systems represent a very interesting attempt to benefit from complementary reasoning styles and computational strengths of both human and artificial solvers. However, because of their composite nature, the design and implementation of such mixed and integrated systems is an arduous and stimulating challenge, likewise for the measurement of their effectiveness and utility. The diversity and complexity of the two involved entities, the human user with her/his unpredictable and sophisticated reasoning and the artificial machine, with its computational complexity and technicality, together with the uncontrollability and uncertainty of the environment, makes it difficult to design precise and effective evaluation methodologies. For these reasons we believe that it is worth investing in the study and design of evaluation techniques that take both the human and the artificial component into account to measure the effectiveness and quality of the overall system. A valid possibility is to exploit existing methodologies from close or related research fields.

In our case, given that our main concern in the development of the system was making it useful for the user, we decided as a first step to conduct a usability study on the Interaction Module. In fact, as already mentioned, one of the first problems we noticed when started the study was users' skepticism. A system difficult to use or with incomprehensible features may increase the inertia with which users get used to novelty and appreciate its benefit. A usability study allowed us to detect existing problems and propose possible solutions to them. In the following a report on this preliminary study is given together with a description of the experiment designed to improve the user-system interaction in MEXAR.

5.1 Methodology

The usability evaluation of MEXAR interface has been conducted by using the "*Think Aloud"* observational technique. The essence of this evaluation technique, which can be considered the best discount usability engineering method (Nielsen, 1993), consists of asking the users to verbalize their thoughts while performing certain tasks and interacting with the system. The experimenter observes silently the interaction session, and records user's actions and thoughts, focusing on the difficulties and problems encountered. A subsequent data analysis phase allows both to identify the positive and negative features of the interface and to propose methods that would solve the identified problems. This technique highlights usability problems in terms of difference between the interaction logic of the system and the model adopted by the user to perform certain actions.

Participants

Four participants took part in our usability experiment. During the development of MEXAR it was not possible to perform experiments directly with real users. As a consequence we performed this usability study with people unaffiliated with the project but having experience in scheduling and planning systems. In particular, two of them were PhD students and two were Research Programmers. Three out of four received training prior to their test, while the forth tester did not receive any training.

Apparatus

The experiment has been conducted on a Personal Computer Pentium 4 - 1,70 GHz - 256 MB RAM under Win XP. The software had been previously tested through a simulation session. During the experiment the interaction sessions have been recorded by using a voice recorder and a screen capture software to register user's thoughts and actions.

Tasks and Procedure

Tasks have been subdivided according to MEX-MDP management phases and designed to completely test system functionalities and services. Three different subtasks have been selected:

- MEX-MDP *Problem Analysis*. Participants have been asked to load an instance of a MEX-MDP problem and inspect problem features (e.g. difficulty, data volume produced by PORs, etc.)
- *Solve* MEX-MDP *problem*. Participants have been asked to find a solution to MEX-MDP instances using the Automated Problem Solver and analyze solution features (e.g. number of Memory Dumps, solution quality, etc.)
- *Select final solution to* MEX-MDP *problem*. Participants have been asked to select a solution considered the best candidate for the execution. They could study the current solution and improve it by using the local search procedure or find completely new solutions through the Solution Explorer. Eventually they had to indicate the final solution considered the best one according to certain quality parameters and their own judgment.

Two training sessions preceded the experiment. They allowed users to exercise the actions needed to carry out the required tasks. Participants received written instructions on tasks and how to carry them out. The experimenter integrated the tasks description by answering additional questions to clarify user's doubts. Training sessions lasted respectively 60 and 30 minutes. The day after the training sessions a detailed description of the tasks has been presented to the users and subsequently they have been asked to carry out each subtask. The experiment lasted about 60 minutes. At the end of the experiment a further interview has been conducted to discover further problems and take note of additional users' advice. Finally the recordings have been analyzed and experiment results have been written in the form of Usability Aspect Reports (UARs).

5.2 Results and Discussion

The final step of the experiment consisted in analyzing the UARs to find out interaction problems and conceive possible solutions. For each problem we thought of a solution aimed at filling the discrepancy between our implementation of the system and the model that the user had of the particular involved aspect. In fact, the proposed solutions derived from a reasoning process devoted to more specifically support user's goal while she/he was carrying out required tasks. A further step allowed us not only to perform a number of local improvements on features of the interactive services, but also to formulate some remarks on the interactive aspects we consider relevant to the design of an intelligent system.

Visualization

MEXAR Interaction Module seems to provide a user with satisfactory representations of the main entities of the MEX-MDP domain. Problem and solution representation provides clear and detailed information that eases the user tasks. The use of payload timeline metaphor is a quick and useful mean to guarantee an immediate overall vision of salient features. On the other hand, an inadequate and sometimes missing description of the algorithm features and parameters caused a general confusion and consequently a skeptical reaction of users who preferred a random selection rather than a reasoned choice. This suggested us to design a more effective dialogue that allows a user to easily and profitably select/configure the algorithm parameters. Given that the final user of the system does not have the needed knowledge to infer the meaning of the algorithms and their parameters, the interaction module should translate this information in a comprehensible way, by using abstractions or metaphors, while hiding technical and useless details (see the *glass box* principle in Section 4.1).

A second interesting issue that is worth emphasizing is the appreciated possibility to choose between different representations of the same information. Users seemed very interested in the alternative graphic representation, as it provides a higher level and more immediate view of the problem and of the solution. The idea of organizing information in different layers has been positively accepted. After consulting the graphic representation, users used the detailed textual representation to check their answers or more precisely understand problem and solution features. This suggests the idea of structuring in layers also the graphic representation. In this way, as a first option a user would see a very high level and concise representation that can be however interactively expanded to obtain more precise and detailed information.

User participation

Users expressed a natural interest in using powerful algorithms that perform repetitive and complex tasks on their behalf. As mentioned in Section 4.1 algorithms perform better on conducting repetitive search steps that are not possible for a human user, while the user usually has more specific knowledge on a domain. The idea of allowing an incremental construction of the solution where a user can contribute with her/his expertise seems to be very promising and in line with the current literature in mixed-initiative system (see Section 4.2). This ambitious and arduous goal should stimulate systems developers in designing tools and functionalities that encourage a profitable human integration in the problem solving.

6. Related Work and Current Directions of Research

Interactive systems for solving planning, scheduling and in general complex combinatorial problems are becoming more and more pervasive in many application areas as space missions, rescue, air campaign or vehicle routing. In the last years, several systems have been proposed for interactive problem solving which can be considered in line with the MEXAR project, even though related with different domains. In this section, in order to compare the MEXAR system with different collaborative schemes we briefly review the main characteristics of some relevant interactive systems proposed in the literature and consider two general principles of interactive problem solving behind the MEXAR and the other systems.

MAPGEN (Ai-Chang et al., 2004) is an interactive system for planning and scheduling for the Mars Exploration Mission, SPIKE (Zimmerman Foor & Asson, 2002) is a tool generating plans of scientific observations for the Hubble Space Telescope. A more general purpose tool is COMIREM (Smith et al., 2003), an interactive system for continuous planning and resource management under complex temporal and spatial constraints. A more specific system is the one developed at the Mitsubishi Electric Research Laboratory [6] (Anderson et al., 2000), which proposes an effective and interactive schema called *human-guided simple search* devoted to the solution of a well-known and difficult combinatorial and optimisation problem, the *capacitated vehicle routing with time windows* (CVRTW) problem.

Broadly speaking all of the above systems follow two general principles for enabling collaborative problem solving schemes between system and user. First, they make solution models and decisions user-understandable, that is, they communicate elements of their internal models and solutions in user-comprehensible terms. This is what we call *glass box* principle. Second, they allow different levels of *user participation*, that is, a solving process can range from a monolithic run of a single algorithm to a fine-grained decomposition in a set of incremental steps. In the MEXAR domain, an example of such step might be the movement of a dumping operation from one window to another one, or the invocation of an explanation procedure on an oversubscribed channel window. These capabilities make a user really involved in the solving process, because she/he can switch from *micro* (local modifications, explanations) to *macro* actions (e.g., the application of a global optimisation algorithm) on the solution and always have a feedback through the user interface.

The so-called *glass box* principle applies to the MEXAR system as well as to the other interactive systems. It is a fundamental issue to allow a user to easily have a representation of the internal system models and decisions, and more important, to have feedback from her/his actions. Generally, the interface is differentiated on the basis of the kind of actions allowed to the user, in other words, it depends on the level of *user participation* within the interactive planning process. Systems as MAPGEN (Ai-Chang et al., 2004) and COMIREM (Smith et al., 2003) promote a problem solving style more centred on the idea of a system as an *intelligent black-board,* where a user can posts her/his decisions and see immediately the effects. In this context, conflict analysis and *explanation* services are fundamental "tools" for collaborative problem solving. Also *what-if* analysis capabilities are useful tools for guiding the search

6 http://www.merl.com

process and compare different partial solutions. On the other hand, even if the previous two systems allow also the use of solving strategies for obtaining a complete solution, systems like SPIKE (Zimmerman Foor & Asson, 2002) or the one developed at MERL lab (Anderson et al., 2000), promote a collaborative problem solving style more centered on the idea of *user guided search.* That is, a user can tune/focalize algorithms towards a given set of subgoals, or composes algorithms in order to make or improve a solution. Obviously, each time an action is performed, the user can have feedback through the interface. The MEXAR system allows a collaborative schema closer to the idea of *user guided search*, in fact, features like the *solution repository* and the graphical comparison for solutions, combined with a *portfolio* of algorithms for finding or improving a solution, promotes this style of interaction.

A future direction of work in the MEXAR project will be to explore methods for increasing the level of user participation. In fact, in order to resolve resource conflicts, currently it is possible only to remove some payload operations from the problem definition. However, this functionality can be enriched with *explanation services* on oversubscribed channel's windows and with the possibility of making available to users an extension of the functions developed for the local search algorithms, such that they will allow to perform local modifications to a currents solution, as the movement of a dumping activity from one window to another.

7. Conclusions

In this paper we described our experience in designing and developing an interaction environment for MEXAR, a decision support system devoted to solving a complex problem in the context of the space mission MARS EXPRESS.

At the end of this unique experience we can say that providing a useful and effective user interaction module, which allows an interactive problem solving shared between the user and the automated system, represents a problem as challenging and arduous as developing efficient automated algorithms.

Our system integrates automated techniques with complex interactive functionalities in order to address the visualization problem to the user, provide her/him with the possibility to personalize the interaction and maintain the responsibility in deciding the final solution.

In the paper we have also described the results of a usability test that helped us to discover limitation in the functionalities but also confirmed the robustness of the direction taken and enabled a number of directions for future work.

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