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Ground Based Operations Support By Artificial Intelligence

Rainer Grun
Manager, Head of System Development MBB/ERNO, 'Bremen West Germany

Albrecht Kellner
Manager, Computer Science Basic Research MBB/ERNO, Bremen West Germany

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GROUND BASED OPERATIONS SUPPORT BY ARTIFICIAL INTELLIGENCE

Rainer Grün, Manager
Head of System Development
MBB/ERNO, 'Bremen
West Germany

Albrecht Kellner, Manager
Computer Science Basic Research
MBB/ERNO, Bremen
West Germany

ABSTRACT

The increasing number and sustained duration of future manned or unmanned space missions, the growing complexity of spacecraft, the increasing variety of payloads and the demand for maximum economic efficiency of space operations will lead to the evolution of large-scale ground based operations infra-structures of increasing complexity and sophistication.

In order to enhance the manageability and safety of operations under these aspects and to limit the amount of highly skilled personnel required, thereby supporting an early economic attractivity of space, the utilization of Artificial Intelligence (AI) as support for ground based operations appears to be a promising method which has received growing attention in recent years.

However, the integration of AI-systems into a complex ground based operations infra-structure, their interaction with large databases, simulation facilities, decision centres and other information sources as well as the need to generate, verify and maintain very large knowledge-bases pose technological challenges which lie less in the traditional conceptional area of reasoning than in the realm of management of Artificial Intelli-gence, and which need to be identified and solved as early as possible.

In this paper, after an outline of the main areas of ground based operations support by AI, also these questions of the management of large distributed AI-systems within a complex communication environment are there-fore addressed and required technology developments indicated which comprise in particular the direct or indirect utilization of databases and simulation facilities as knowledge sources for large AI-systems.

1. INTRODUCTION

The future European space programs represent a new dimension for the involved community and will require a ground infrastructure of a new order of magnitude. The greater size of the ground based end-to-end operations and verification infrastructure (GEOVI) and its long life cycle needed to support these new programs together with a large engineering and user community dispersed in many countries pose a formidable technological, financial and management challenge resulting in the need to harmonize the GEOVI, to identify commonalities, to implement standards, to develop common elements (HW/SW) and be able to re-use past investments, but also to implement new elements and new technologies where required to increase the effectivity and reduce cost.

Of these new technologies, Artifical Intelligenz (AI) appears to be a promising candidate which has received growing attention in recent years.

After a brief overview of the future European flight and ground infrastructure showing the challenges involved and the need for advanced technologies, a description of the major potential applications of AI is given.

The prime purpose of this paper, however, aims beyond a mere enumeration of such applications: in order to realize these applications certain technological issues have to be solved which are quite typical for the utilization of AI in Space Technology and which do not seem to have received much attention as of now.

It is this aspect which will be addressed in the final part of the paper in order to clarify the preconditions which need to be met for a successful utilization of AI in the future European ground infrastructure.

2. THE SCOPE OF THE FUTURE EUROPEAN GROUND INFRASTRUCTURE

The scope of the future European ground infrastructure is derived from

2.1 The Future European Flight Infrastructur

The European Space Agency (ESA) is proposing a coherent, long-term program in manned and unmanned space operations.

Main parts will be the four-element European space station COLUMBUS, the Ariane 5 heavy-lift launcher, the spaceplane HERMES and the European data relay satellite (EDRS).

COLUMBUS

The four elements of COLUMBUS are:

- The Attached Pressurized Module (A-PM), permanently attached to the international space station (ISS)

- The Man-Tended Freeflyer (MTFF). The term man-tended means the freeflyer would operate unmanned during the majority of its time in space, but could be manned during limited periods for reconfiguration, repair, servicing, exchange of experiments, samples, equipment and on-orbit replaceable units (ORU)

- The Polar Platform (PPF) capable of carrying multipurpose payload e.g. Earth observation instruments and communication- and navigation payloads, placed in a Sun-synchronous polar orbit. Main platform elements are a propulsion module, a utility module and the payload module itself.

- The co-orbiting platform (CPF). It is considered to use an enhanced EURECA platform as a co-orbiting system with the space station. The enhanced platform shall stay for more than one year operational with payload exchange on ground but growth capability for on-orbit servicing.

ARIANE

As space transportation system, Europe has the Ariane 2 and 3 in service while the increased-lift Ariane 4 will be introduced this year. Under development is the heavy-lift launcher Ariane 5, to be capable of carrying unmanned and manned payload into orbit. The man-rating of Arine 5 is a new dimension for Europe's space agencies and industry.

HERMES

The future European manned spaceplane HERMES will be launched by Ariane 5. It shall be capable of performing a number of missions including servicing of space station or orbital platforms and autonomous flights for various science and observation applications. Safety and rescue aspects of HERMES as well as a controlled reentry are main requirements to be solved. HERMES will land on a normal runway in Europe.

In addition launchers of the next generation such as Hotel and Sänger are studied to be an integral part of the future infrastructure.

EDRS

The European DRS, positioned in a geosta-
tionary orbit allows an enormous increase in
realtime communication capability of low
earth orbiting (LEO) spacecraft with the
ground. The DRS system intended to be
launched by Ariane 4 includes the payload
operating both at S-Band compatible with the
NASA TDRSS and Ka-Band for high data rate
services.

Four simultaneous independent links to four
different LEO spacecrafts are foreseen, two
in each frequency band as a baseline. The
feasibilty of multiple access at S-Band is
considered as an option.
The EDRS will provide information (data,
video, voice) transmission, telemetry,
telecommand and ranging services to the
future European space programs.

EURECA

The European Retrievable Carrier is a free
flying low earth orbiting platform designed
for an operational mission duration of six to
nine months. It will be launched and re-
trieved by the NSTS. The EURECA-1 platform
will carry 15 payloads containing more than
70 individual experiments. All experiments
will be autonomously controlled on-board, but
initiated by the master schedules (MS), which
also be used to change operations profiles.

SATELLITES

A. Scientific Satellites

Besides the spacecraft already in orbit e.g.
IUE, GIOTTO there are launches scheduled for
1988/89 in particular for Hipparcos and
Ulysses. The Soho/Cluster program is under
preparation with launch dates in the 1993/94
timeframe which is about one year later than
the scheduled ISO spacecraft launch. A launch
date for ROSAT has to be defined.

B. Earth Observation

The Meteosat spacecrafts provide services to
the European Meteorological community
since 1977. Second generation Meteosat
spacecraft are in preparation to guarantee
uninterrupted service until mid 1990s.

ERS-1 is scheduled to be launched in 1989
into a polar orbit.

C. Telecommunications

ECS and MARECS satellites are operational
since beginning of the 1980s. Further ECS
spacecraft will be launched. The AIV phase
of Olympus is being performed presently.
Already mentioned was the EDRS in relation-
ship with COLUMBUS. A European navigation
satellite system NAVSAT is being studied.

TV-SAT, TDF-1 and DFS Kopernikus are addi-
tional spacecraft to be mentioned in this
category.

2.2 Future European Ground
Infrastructure

The stepwise establishment of the European
Space infrastructure corresponding to the
future flight infrastructure described above
requires a ground based end-to-end operation
and verification infrastructure (GEOVI) of a
new order of magnitude. All elements of GEOVI
have to work together in a coherent and well
adjusted way. The three segments of the
end-to-end data system (on-board, space/-
earth, terrestrial) cannot be seen separately
because when one segment is approached, the
other two cannot be discussed without per-
turbing the functions of the entire data
system.

On-board formatting, acquisition, processing, archiving, ground to space and space to ground data transmission, on-board/ground command and control, terrestrial data distribution, processing, storage, retrieval, exploitation centralized and decentralized are the main functions of the extremly complex data system.

Due to the greater demand of future programmes for automatic verification and simulation equipment together with more complex spacecraft such as COLUMBUS and HERMES, the complexity of future EGSE will be much higher than that of today's equipment.

Individual program needs and required user support ground segments exceed the very tight budgetary frame available for the European space community (agencies and industry). Investments are necessary for industrial development facilities to support the AIV phase, support facilities for development and operation, launch and landing facilities, operations facilities for mission and payload control and payload data facilites for data dissemination, archiving, retrieval etc..

Operational cost including maintenance and refurbishment will exceed the investments by far until the year 2000.

3. GROUND BASED OPERATIONS BY ARTIFICIAL INTELLIGENCE

Obviously the future European space programs summarized in the previous chapter represent a new technological and organizational dimension for the involved community and will require a ground infrastructure of an unprecedented order of magnitude concerning cost, manpower and technological complexity. This means that methods and ways to confine the dimensions of these aspects become a major issue and require careful analysis prior to the build-up of the ground infrastructure.

Apart from means such as harmonization of the ground infrastructure, rationalization of industrial capacities etc., the utilization of new technologies and particularity Artificial Intelligence (AI) as support for ground based operations appears to be a promising method to confine manpower and cost and to enhance manageability and safety of operations.

Moreover, as will be shown in the following chapters, the complexity of systems and operations might be more than human operators can handle in the time frames required and make the utilization of AI mandatory regardless of the considerations given above.

Potential and challenges involved in the application of AI will be discussed in the following chapter.

3.1 Suitability of AI: General Considerations

In order to estimate the suitability of AI as means to support the ground based operations infrastructure from a general point of view, at first a definition of AI will be given which differs from most attempts at defining AI in that it is based on the pragmatical aspects of information processing rather than on the more philosophical issue concerning the term "intelligence".

According to this definition, AI is primarily characterized by

a) Generalization of processed information: In AI-systems the set of data types processed is augmented from mere numbers representing the predominant data types in conventional systems to data such as facts, relations, images and abstract knowledge encoded in complex structures, mainly in symbolic form.

b) Generalization of information processing

This expansion of data types calls for a transition to new information processing methodologies (such as feature recognition, pattern matching, data driven search, etc.) also characteristics of AI.

c) Learning

AI-systems generally realize a type of passive learning capability corresponding to the human ability to absorb more knowledge throughout his life quite easily without the need to restructure his thinking mechanism each time, and to apply this knowledge in a data-driven way, i.e. the brain automatically accesses the type of knowledge appropriate to the type of problem at hand. In AI-systems this is achieved by an architectural separation of the software into a knowledge base into which new knowledge can be entered as easily as data into a database, and a generic inference engine representing the context-driven reasoning power of the system which stays unchanged when the knowledge-base is modified.(Active learning, i.e. the ability to automatically evaluate experience and generate new knowledge and knowledge processing methods is still too much a research topic to be included in the present considerations.)

Due to the recent explosion in computer performance, this generalization of information processing and the corresponding opening of new realms of computer applications formerly only accessible to the human intelligence happened rather suddenly and surprisingly, and this might be one of the reasons why the term "Artificial Intelligence" has been so widely established. Recently, however, this term is increasingly being substituted by the more appropriate terms "Knowledge Processing Systems" or "Knowledge-based Systems".

To see how this expanded computer applicability can be used in support of ground based operations activities, one should note that in contrast to the mainly algorithmic information processing used to generate a certain output from a given input, which is the typical field of application for computers to-day, the reversed infromation processing, i.e. the identification of input data necessary to generate a required output, so far was confined to treatment by the human intelligence only.

A typical example for algorithmic data processing is the simulation of system behaviour by models which can be used, e.g. to identify the sensor data output given a certain component failure as input.

The inverted process, i.e. the identification of the failed component(s) given a certain sensor behaviour, cannot be performed by simply "rewinding" the algorithms of the model since each of the individual sensor readings can be indicative of many anomalies at the same time. Instead, only a search process based on knowledge about the interaction of the components of the system, can provide the desired answer.

Thus it becomes apparent that intricate failure diagnostic processes frequently demanding long sessions of experts' discussions could typically be supported by AI-systems.

Similar considerations could be applied, e.g. to object recognition, plan generations, system design etc.. For example, a suitable model could easily generate a resource consumption profile as output for any given experiment timeline used as input. As soon

as the inverted process is required, i.e. the generation of a timeline constrained by a given resource availability, algorithmic solutions fail and knowledge-based search and other methods characteristic of AI have to be applied (Fig. 1).
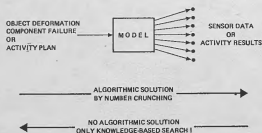

Fig. 1:   Conventional vs. AI-Based Methods

Another major feature of AI-systems matching the requirements of ground based operations information processing is implied by the dynamic configuration of space segments (particularly of COLUMBUS and EURECA) calling for continuous updating of software. Obviously this is considerably facilitated by the passive learning capability of AI-systems mentioned above, whereby new configurations can be "learned" without the need to change the kernel code.

3.2 Applicability of AI: Instances

In the following, an overview of the major instances of ground based operations support by AI which can be envisaged on the basis of the general discussion above will be given.

For greater transparency, these instances are categorized into the four classes

-   Cognition

-   Analysis

-   Synthesis

-   Man-Machine-Interface (MMI)

For interest's sake it might be mentioned that these classes, if supplemented by the class of control-systems, represent the complete set of behavioural elements of an autonomous system capable of symbiotic co-operation with man.

In Fig. 2 the functional cycle of such a system containing the described elements is displayed.

It depicts the cognitive element which generates input data for the analysis of these data in the context of the overall situation. This again is used to synthesize an activity plan which is executed by the control element. The observation of the outcome of this activity by the cognitive element closes the functional cycle. Transparency of these autonomous activities and override capabilities to man are provided by an efficient man-machine interface.
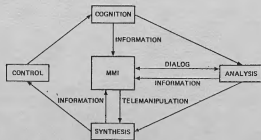

Fig. 2:   Functional Cycle of an Autonomous System

1. Cognition

Whereas cognition, the ability to recognize objects and their behaviour from object-generated sensor data, will certainly play an important role for in-orbit robotics and autonomous RVD, its role in a ground based operations infrastructure will probably not be predominant, except possibly for tracking support by using knowledge-bases about the tracked abject's dynamics . and signal-reflecting characteristics and appropriate inference mechanism to estimate attitude and dynamic behaviour.

2. Analysis

A major application of AI will be in the area of analysis and interpretation of the great amount of data generated by systems and payloads and it is to be expected that a considerable reduction in manpower and processing time will be achieved by the utilization of knowledge-based systems, e.g. for

- check-out

- monitoring and situation assessment

- failure detection

- payload data analysis

Particulary for the first three instances the required technology of knowledge-based systems in fairly well established in the form of expert systems capable of deducing system states and failures from sensor data patterns as described in 3.1.

This technology could also be used to support the user in payload data analysis, e.g. to identify significant results and give early indications of necessary control adjustments etc. to enhance the success of scientific experiments.

3. Synthesis

Probably the most important application of AI in the future ground based operation infrastructure will be in the area of synthesis, i.e. in the automatic generation of activity sequences and schedules for, e.g.

- integration planning

- turnaround planning

- check-out planning

- multiple timeline generation for test scenarios

- mission planning and re-planning

Due to the complexity of spacecraft and payloads, the multitude and diversity of user requirements and constraints these tasks are extremly time-consuming and require considerable manpower so that it is quite obvious that efficient AI-systems capable to execute or support these tasks could indeed prove to be a major factor in ground based operations cost reduction and efficiency enhancement.

Moreover, the complex and highly iterative task of continuously generating timelines thoughout the lifetime of COLUMBUS and the need of fast re-planning in case of changes in resources and other constraints might turn out to be an intractable task for the human operator within the permissible time frames, so that the use of sophisticated planning systems might well become mandatory for technical reasons also.

Another synthesis task for AI systems will be the automatic generation of command sequences for spacecraft control, e.g. for fast recovery actions from complex anomalies.

Together with the failure diagnostic systems mentioned above, the systems would provide intelligent operator's assistants which, initially, would operate in an online but open-loop mode as intelligent consultant systems.

4. MMI

The higher the degree of system complexity and autonomy, the greater the need of transparency of the system's behaviour and ease of controlling it to the human operator. This calls for efficient MMI techniques able to

- explain user's queries concerning the system's reasoning process

- reduce data overload to the significant information content

- provide associate information based on an understanding of the user's intent

- allow for high-level and flexible man-machine communication, particularly involving natural language understanding

At the same time systems featuring these MMI characteristics can serve as valuable aid to crew training, since such systems display the contents of their knowledge-bases and their reasoning processes in user-friendly ways and can be used to compare crew reactions with the system reactions based on large knowledge-bases premeditated by many experts.

4. MAJOR TECHNOLOGICAL ISSUES

When speaking about potential utilization of AI in space technology, the focus so far has been mainly on the availability of sufficiently advanced reasoning mechanisms required for applications such as these mentioned in the previous chapters. Typically, these methodologies are demonstrated by stand-alone prototype systems with usually very limited knowledge-bases.

However, for a practical utilization of AI within the ground based infrastructure, aspects have to be considered which add quite a new dimension to the considerations mentioned above, which arise directly from the enormous complexity of the ground infrastructure and space segments into which AI systems have to be integrated as well as from the enormous amounts of knowledge which need to be generated, processed within reasonable time frames, continuously updated with the changing space segment configurations, and maintained. Therefore, after a brief overview of the state of the art of AI technologies applicable to ground based operations support, these aspects will be addressed in more detail.

4.1 AI Technologies

Concerning the conceptual side of artifical reasoning and knowledge processing, the present state of the art has reached a fairly good demonstration level in all four categories listed above, i.e. cognition, analysis, synthesis and man-machine interaction. Of course, in many areas intensive research is still required to reach practical applicability, such as in the case of feature recognition and natural languages understanding. However, particularly in the area of expert systems for failure diagnosis and to a certain extent also in the area of automatic planning, concepts are quite advanced and ready for practical application, as proved, e.g., by an increasing utilization of such AI systems in terrestial industry.

As indicated above, an application in space technology however requires the satisfaction of special preconditions as a result of the particular characteristics of the communication infrastructure required for spacecraft operations.

4.2 Knowledge Management

In order to be effective, AI-systems for ground based operations support need to be able to access and process extremly large amounts of data and knowledge.

For example, in order to automatically generate mission plans for the elements of COLUMBUS, an AI-based planning system would have to have at its disposal descriptions of thousands of activities each representing large data structures, the interdependencies between all activities, all resource profiles, constraints due to systems, subsystem and payload characteristics, . technical, scientific, financial and political priorities, experimenter's requirements, heuristic rules for activity selection, etc.. Similarly the knowledge-bases of expert systems for the support of spacecraft control will contain enormous amounts of knowledge about the spacecraft's configuration, behaviour and possible anomalies, control procedures, contingency actions, detection of failed sensors, etc..

The point to be made here is that in order to be of real value and to be accepted by the personnel, AI-systems must have to allow for a large coverage and thus have to be provided with large knowledge-bases indeed.

This raises several questions concerning the "knowledge management", i.e.

- effort and cost of generating, verifying, updating and maintaining such large knowlege-bases.

- methods to allow for fast access and efficient processing of the stored knowledge.

Regarding the first questions, the fact that large portions of the required information and knowledge is already being provided by the ground infrastructure becomes of major importance.

For example, practically all information about the activities to be scheduled by an automatic mission planning tool are part of the mission databases, and spacecraft simulators represent huge ready- made knowledge-sources for spacecraft control support systems.

If these knowledge-sources could be utilized by AI-systems, the problem of knowledge-management could be delegated to a large extent to the development, verification and maintenance activities of databases and simulators which are an integral part of the ground infrastructure anyway, thus eliminating the costly need of a parallel development, verification and maintenance of additional knowledge-bases.

However, the technology whereby the information present in databases and simulators as given in the ground infrastructure can be extracted and reformatted to be utilized by AI-systems is still under development.

It is the purpose of this paper to point out the need for a concentrated technological effort in this area of Artificial Intelligence.

Ideally a technology is required whereby any database or simulator can be transformed into suitable knowledge-bases or used as such. This might sound exaggerated, but failure to produce this technology might either confine the benefits of AI to small and isolated applications or call for manpower allocated

to knowledge management of equal size as that required for building the simulators and databases.

The second question posed above concerning the performance of AI systems processing large knowledge-bases might be less severe due to growing computer power. However, methods of greater efficiency than those represented by the classical symbol-manipulating method of AI should also be investigated [1].

4.3 Integration

Due to the distributed, highly interactive nature of the ground based operations system with various decision and control centres of different hierarchical levels as described, e.g., in [2], an introduction of AI-systems for ground based operations support necessarily implies a high degree of networking of these systems.

Interactions between planning, diagnostic and control support systems with intelligent man-machine interfaces, databases, simulators, or with personnel of element contractors and other knowledge-sources and interfaces have to be implemented.

This again leads to the question of interaction of AI-systems and knowledge-sources such as databases and simulators discussed above but it also raises the question concerning the functional synchronization of a large set of distributed, partially or completely autonomous intelligent systems which might in itself call for an intelligent meta-control system to manage, e.g., the logical sequence of diagnosis, simulation runs for prognostic purposes and decision on failure recovery actions, at the same time allocating priorities to knowledge-source access in case of collision with other processes demanding access to the same facility at the same time etc.

Although the introduction of AI into the ground infrastructure will certainly proceed in a gradual, incremental way it should be pointed out that also these aspects implied by networks of intelligent systems which will eventually evolve demand timely consideration.

5. CONCLUSION

Considering size and complexity of the future European ground infrastructure and the technological, financial and management challeges implied thereby, the need for an assessment of new technologies as means to support operations and reduce cost becomes apparent.

In this respect Artificial Intelligence appears to be a promising candidate providing a large variety of applications discussed in this paper. It has to be stressed, however, that the specific nature of the ground infrastructure and the need to generate, verify, maintain and process vast amounts of knowledge by the various AI-systems necessitate a timely and intensive technological emphasis on aspects related to distributed AI-systems and knowledge management.

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