ATOS-1: DESIGNING THE INFRASTRUCTURE FOR AN ADVANCED SPACECRAFT OPERATIONS SYSTEM[1]

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1. An alternative title adapted from related work in the area of concurrent engineering (Ref. 1) is "Towards a Medium for Collaborative Space Mission Design and Operations"

ABSTRACT

The space industry has identified the need to use artificial intelligence and knowledge based system techniques as integrated, central, symbolic processing components of future mission design, support and operations systems. Various practical and commercial constraints require that off-the-shelf applications, and their knowledge bases, are reused where appropriate and that different mission contractors, potentially using different KBS technologies, can provide application and knowledge sub-modules of an overall integrated system. In order to achieve this integration, which we call knowledge sharing and distributed reasoning, there needs to be agreement on knowledge representations, knowledge interchange formats, knowledge level communications protocols and ontology. Research indicates that the latter is most important, providing the applications with a common conceptualisation of the domain, in our case spacecraft operations, mission design and planning. Agreement on ontology permits applications that employ different knowledge representations to interwork through mediators which we refer to as knowledge agents. This creates the illusion of a shared model without the constraints, both technical and commercial, that occur in centralised or uniform architectures. This paper explains how these matters are being addressed within the ATOS programme at ESOC, using techniques which draw upon ideas and standards emerging from the DARPA Knowledge Sharing Effort. In particular, we explain how the project is developing an electronic Ontology of Spacecraft Operations and how this can be used as an enabling component within space support systems that employ advanced software engineering. We indicate our hope and expectation that the core ontology developed in ATOS, will permit the full development of standards for such systems throughout the space industry.

Key Words: Knowledge Sharing, Ontology, Knowledge Based Systems, Mission Information Base, Spacecraft Operations, Mission Design and Planning

1. THE ADVANCED TECHNOLOGY OPERATIONS SYSTEM

During the past few years the European Space Operations Centre (ESOC) of the European Space Agency (ESA) have carried out a number of projects to demonstrate the feasibility of using advanced software technology, in particular artificial intelligence techniques and knowledge based systems, to support spacecraft operations. Although these applications have been successfully tested in isolation and for selected or simplified subsets of required mission functionality, there are a number of advances which must be achieved before AI techniques can be fully exploited in future mission systems, namely, ***integration*** of the applications into a single system with ***consistency*** in information model and user interface, together with ***generalization*** of the applications so that they are mission independent. Unless generalisation is achieved, the cost of development of such systems will be a stumbling block to operational deployment.

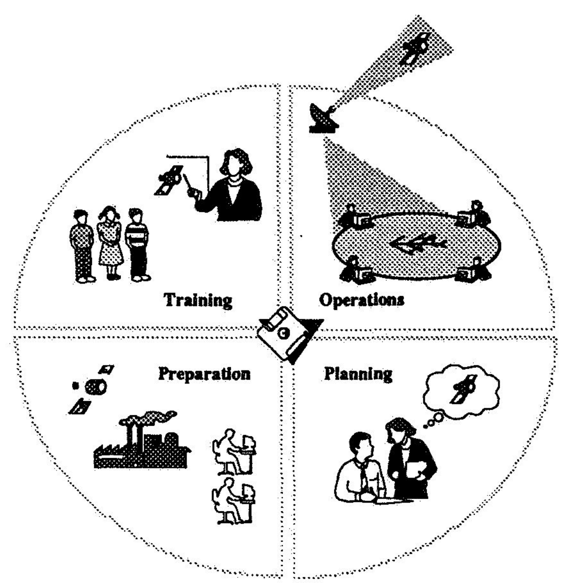

Figure 1 The Advanced Technology Operations System (ATOS)

In order to achieve this goal ESA has initiated the Advanced Technology Operations System programme (ATOS) which will develop the system concept and infrastructure to support spacecraft operations systems which utilize advanced software technology and the development of advanced application modules (AAMs) to support: Mission Preparation, Mission Planning, Computer Assisted Operations and Advanced Training.

Logica is leading the first project in the ATOS programme, ATOS-1, which is tasked with the goal of designing and prototyping software to demonstrate the overall system concept and to provide the formal specifications of the ATOS technology infrastructure, which is required as inputs to the other ATOS phases. Key to this endeavour is the formal specification of an ***Ontology of Spacecraft Operations.*** An ontology is a formal specification of the knowledge structures that can be used to model a domain, in our case the domain of spacecraft operations. Terminology and relationships between entities in the domain are explicitly defined. This paper explains the role of ontology in achieving ATOS goals. We believe that the approach described has wide applicability in acting as a catalyst for the exploitation and development of advanced mission support applications throughout the space industry and elsewhere. Recognising the significance of agreement on definitions is the key to moving knowledge based systems off the side lines and into mainstream mission support and operations. The aim is to create a medium in which collaborative mission design and operations can flourish.

As mission lifetimes extend and mission objectives and payloads become increasingly complex, advanced functionality must be made available to mission staff, to help manage the complexity and to provide efficient and accurate knowledge transfer between mission phases and between mission staff. ATOS technology is needed right now, but must be provided in a form acceptable to users. ATOS concentrates upon providing mission support power tools, rather than applications aimed at removing close human involvement in the mission operations process.

1.1 The Benefits of ATOS

ATOS aims to improve the operations viewpoint, the mission viewpoint, the human viewpoint and the technology viewpoint.

Operations require improved user interface facilities, particularly in terms of representation and manipulation of spacecraft models and operational procedures. Support to the user must include on-line documents, intelligent assistance and improved procedural reliability and thoroughness.

The mission requires efficient configuration, harmonisation of practices and minimisation of manual interfaces between currently disparate activities. The mission requires more flexibility in the allocation of manpower, tasks and skills.

The technology perspective dictates flexibility in the allocation of computer resources to enable distributed and scalable computing, together with a strategy that will provide open reusable and portable software applications.

All these matters will be addressed in the ATOS programme. The current phase, ATOS-1 is concentrating upon the knowledge that comprises a mission and is finding ways to store it, preserve it, reuse it and communicate it. This is known as ***Knowledge Sharing,*** which is a new technology for the 1990's which will enable a new range of sophisticated applications to be developed that exploit and interchange ***knowledge as a valuable asset.***

The ATOS-1 project began work by looking at various initiatives in the formalisation of standards for platform level portability of knowledge. It soon became apparent that this in itself would not achieve ATOS goals and recent work has focused upon knowledge level (Ref. 2) representations and on the construction of ontologies, which formally define the knowledge structures that comprise a domain, in our case, spacecraft operations.

Further information regarding the motivation for ATOS, current activities in the programme and expected future work can be found in a companion paper (Ref. 3).

2. THE NEED FOR KNOWLEDGE SHARING, REUSE AND INTEGRATION

2.1 The Nature of the Problem

The space domain, like most others, has seen the development of a wide range of applications of knowledge-based systems during the past few years. Although many of these applications were only experimental prototypes, an increasing number are being deployed operationally (Ref. 4) or are entering pre-operational trials (Ref. 5).

In general, building a knowledge-based system involves developing a new knowledge base from scratch. This has been true of prototype applications in the space industry, with different groups building applications for the same agency, or contractors developing their knowledge bases in isolation. The duplication of effort involved has already been significant and will be a major stumbling block to operational deployment as application demands require larger and larger systems to be built. It is therefore vitally important that we establish a mechanism to enable knowledge to be reused within related applications. Operational versions of such applications will be considerably more complex than the prototypes built to date and include much larger bases of knowledge. This underlines the need for reuse of that knowledge and the applications which use it.

In addition to ***reuse of knowledge*** there are two further significant impediments to the development and deployment of major KBS-based spacecraft operations systems:

- *Knowledge sharing*; allowing separate physical knowledge-based components within an overall system to share knowledge. For example, a diagnosis application and a monitoring application need to share the same overall model of system structure and behaviour, but may need to use different knowledge representations.

- *Integration of knowledge-based applications*; allowing the run-time exchange of knowledge between applications. For example, allowing an application to notify others of new things it has deduced as a result of changes in the operating environment.

It is finding solutions to these three factors which will open the door to a new generation of spacecraft operations systems incorporating advanced technologies.

Other aspects of knowledge based system technology, such as validation and verification are important but, in the context of the ATOS-1 project must be seen in a secondary role. Such activities are generally associated with KBS methodologies which are used to structure application development and guide the process of domain expert knowledge capture. These aspects will be important to future ATOS phases but are not a prime concern in ATOS-1, which must define the knowledge structures and semantics (ie not contents) to be used by applications to enable knowledge sharing and to decouple knowledge from inference mechanisms, the latter being a major source of impediment in achieving knowledge sharing in previous generation KBS systems.

2.2 Foundation for a Technological Solution

The problems identified with respect to reuse, sharing and communication of knowledge within the ATOS-1 project can be addressed by providing technological solutions in the following areas.

2.2.1 Knowledge Interchange

If a knowledge-based system is to make use of an existing knowledge base or library, or to interchange knowledge with another system, then the knowledge must either be encoded in the system's representation or be translatable into that language.

Given that for many applications practical efficiency is made possible by using a special purpose representation, it is impractical to expect a universal representation language to become available which will meet the needs of all space applications. Two different applications may wish to represent the same knowledge using different structures in order to improve the efficiency of reasoning in each.

The major initiative in this area is the Knowledge Interchange Format (KIF) (Ref. 6) which is being developed within the DARPA Knowledge Sharing Effort (Ref. 7). KIF has been developed for use as an interlingua (ie intermediate language) for communicating knowledge between computer programs which use different knowledge representations.

Within the ATOS-1 project we are adopting KIF as our knowledge interchange language.

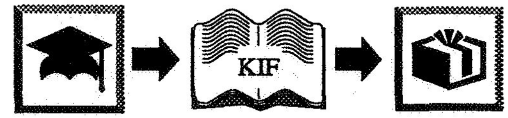

Figure 2 KIF as an interlingua

2.2.2 Standardised Knowledge Representations

KIF is not intended to be used as a representation for direct manipulation by a computer system (although it can be). A further significant problem therefore to achieving practical knowledge sharing at present, even within close families of languages, is therefore that for each representation paradigm used by applications, eg. frames and semantic networks, there are a wide range of practical implementations of that paradigm. Each implementation has its own idiosyncrasies, which means that knowledge represented using one variant is difficult to share with the user of another.

This aspect of knowledge sharing and reuse is being addressed by the development of standards for knowledge representation languages, such as the IMKA initiative (Ref. 8) and the KRSS initiative within the DARPA Knowledge Sharing Effort (Ref. 7), which are working towards standards for frame-based representation systems and KL-ONE derivatives (Ref. 9) respectively.

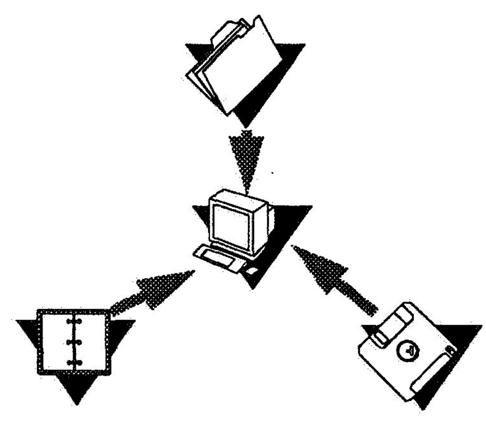

Figure 3 The need to standardise within a representation paradigm

2.2.3 Communication of Knowledge

A further aspect of the problems faced by ATOS with respect to knowledge sharing is enabling the run-time communication of knowledge between programs, ie. Enabling programs to exchange knowledge and to query each other with respect to the state of their knowledge bases.

Within the research community the major development in this area is KQML (Knowledge Query and Manipulation Language) (Ref. 10). KQML is a high-level language and a set of protocols which can be used by software systems for the run-time sharing of information and knowledge.

KQML is already being used as a knowledge communication in two testbeds: the Palo Alto Collaborative Testbed (Ref. 1) which is in the domain of concurrent engineering and the DARPA/Rome Planning Initiative which is concerned with military transportation planning. Within ATOS-1 we intend to develop a spacecraft operations testbed which will investigate the applicability of KQML to the domain of mission control.

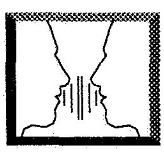

Figure 4 Communication at the knowledge level

2.2.4 Shared, Reusable Knowledge Bases

Despite the practical problems which can be overcome using developments such as KIF and KQML there still remains a fundamental problem with respect to knowledge sharing: the semantic ***content*** of a knowledge base. This requires that developers, and hence the applications they develop, have a common conceptualisation of the domain in which they are operating. That is, they must model those things which are important to their task in terms of the same objects, processes, relationships etc. Such a model is called an ontology.

Figure 5 A common ontology in the minds of users and machines

In adopting a certain set of concepts and their relationships a program makes a number of ontological commitments to a particular conceptualisation of the domain. If a number of applications adhere to the same conceptualisation they are said to have a ***common ontology***. It must be stressed that in defining an ontology one is attempting to explicitly capture the formal semantics of a data model. This is therefore fundamentally different from the aims of the various standards being set in place for integration of object and database systems, which typically concern the format and usage conventions of information rather than the meaning of the knowledge implied by the information.

A major objective of the ATOS-1 project is to establish a common ontology for use by applications in the spacecraft operations domain, ie. ***an Ontology of Spacecraft Operations***. This is discussed further in section 4.

3. AN OPERATIONAL CONCEPT

The ATOS objective is the establishment of an infrastructure by which intelligent knowledge based applications (KBS) interact at the ***knowledge level***, that is they interact with respect to an explicit shared and agreed model of the domain of spacecraft operations. This idea is illustrated in figure 6:

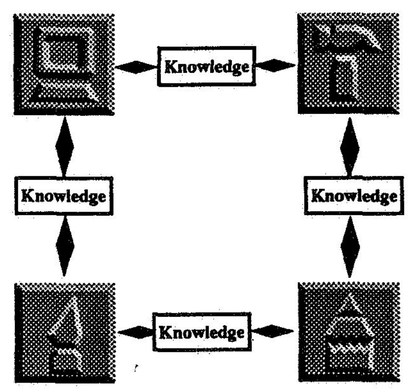

Figure 6 Applications interacting at the knowledge level

Since applications are unlikely to be developed according to a completely consistent common ontology and use identical representation systems, this can only be achieved if the applications interact through a ***Distributed Access Service*** (DAS) based on cooperating knowledge agents that themselves adhere to a consistent ontology of spacecraft operations. The complexity required within each agent will depend upon how far the applications deviate from the ontology. Agents will perform functions such as translation of query forms as expressed by applications into the standard ontological model. This idea is illustrated in figure 7:

Knowledge agents will mediate between disparate applications that employ heterogeneous knowledge representations, reasoning methods and query forms. The shared ontology that forms the fabric of the infrastructure will provide the means by which applications will access a logically unique repository of mission information, the so-called ***Mission Information Base*** (MIB). The MIB itself is likely to be highly distributed and itself comprise heterogeneous representation systems (relational, object oriented, logic-based). In certain cases applications will themselves retain MIB partitions locally for specific purposes, with the express aim of optimising knowledge manipulation and ensuring that the most appropriate representation for the specific reasoning task is used.

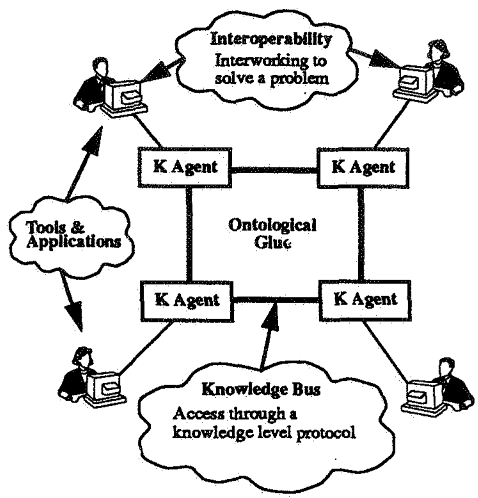

Figure 7 A distributed access service

Irrespective of the location of knowledge resources and of reasoning capability, each application will have access to the entirety of all mission knowledge and be able to call upon the deduction capabilities of all applications through the medium of knowledge communication. The shared ontology that comprises the fabric of the architecture will ensure that the semantics of mission knowledge are consistent between all applications.

The creation of such an infrastructure for a wider domain would be a formidable undertaking indeed. It is our view however that the domain of spacecraft operations, and current ESOC required functionalities, is of sufficiently contained scope to ensure that the development of the core ontology remains a tractable problem.

ATOS applications that adhere to the ontology will be ***generic, mission independent, human engineered tools,*** tailored for specific mission design or operational tasks. Examples include planning and scheduling, diagnosis and trouble shooting, monitoring and control, engineering modelling and simulation, schedule and procedure execution.

4. THE ONTOLOGY OF SPACECRAFT OPERATIONS

The ATOS-1 project will establish a core ontology of spacecraft operations. This will define the objects, relationships, processes etc. required to represent core knowledge in the spacecraft operations domain.

The core areas which are being covered within the ATOS ontology include: Planning and Scheduling, Engineering Modelling, Monitoring and Control, Diagnosis and Troubleshooting, Flight Dynamics and User Interface Model. Within each area a number of sub-topics have been identified and these will form logically self-contained units of ontology, called theories, which can be used by applications in a discrete fashion if required.

```
(define-class system (?s)
    "System is the root class of all systems. A system may be a
primitive object or consist of a number of other systems. It doesn't
make sense to allow instances of system itself so it is constrained to
be an individual."
:def (individual ?s))      ;from KIF ontology - not a set


(define-relation part-of (?s1 ?s2)
    "s1 is a part of s2. The part-of relation is limited to a system
and its immediate subsystems, ie. It is not transitive. This helps to
view the overall system at differing levels of abstraction which can
be useful in modelling to limit the detail to that required in a partic-
ular situation. A system cannot be a part of itself, ie. Irreflexive."
:def (and (system ?s1)
          (system ?s2))
:axiom-def    (and    (not (transitive part-of))
                           (irreflexive part-of))))


(define-relation components (?s ?c)
    "Components relates a systems to its direct components, ie.
The systems ?S for which (part-of ?S ?s) holds. For a system which
is a primitive object components is the empty set. A system cannot
be a component of itself, ie. Irreflexive and a system cannot be a
component of a system that is a component of it."
:def (and (system ?s)
          (system ?c))
          (part-of ?c ?s))
:axiom-def    (and    (not (transitive components))
                           (irreflexive components))))
```

Figure 8 Example of ontology written in Ontolingua

In selecting a representation and tool for developing the ontology a number of requirements were addressed. The most significant requirements in the decision process were:

- **Well-defined semantics** - the ontology will form a resource to be used by many application developers, this means its interpretation must be unambiguous;
- **Electronically readable** - the ontology will need to be exchanged by a variety of developers

and worked upon independently at different sites;

- **Translatability** - the ontology will be required in many different forms, dependent upon the particular tool being used by the developer.

The representation that has been adopted is Ontolingua (Ref. 11). Ontolingua is a language and a supporting translation architecture which has been specifically designed for the development of portable ontologies. Ontolingua is being developed as part of the DARPA Knowledge Sharing Effort, unifying the predicate calculus representation of KIF (Ref. 6) with the concepts found in object-centred knowledge representation systems. KIF is based on predicate logic, with a formalised mathematical foundation. Ontolingua provides the means to structure assertions in object-centred hierarchies with inheritance via standard primitives for defining classes and relations.

An example of part of the spacecraft operations ontology is given in figure 8. It illustrates a class and two relations used to form ontological commitments between applications wishing to adopt a common model for structuring the spacecraft model hierarchically.

To help convey the idea of the ontology further it is worthwhile considering an alternative perspective from the application-oriented (ie by Ontolingua "theory") partitions discussed earlier. This is to view the ontology as consisting of layers of increasing specialisation of generic abstract concepts such as "process", "event" etc. These are specialised firstly so as to form abstract domain concepts, such as system, device, sensor etc, and then specialised into generic spacecraft operations concepts, eg. telecommand, solar panel etc. Finally this is specialised in terms of any agency-specific terminology or conventions. This is illustrated in figure 9.

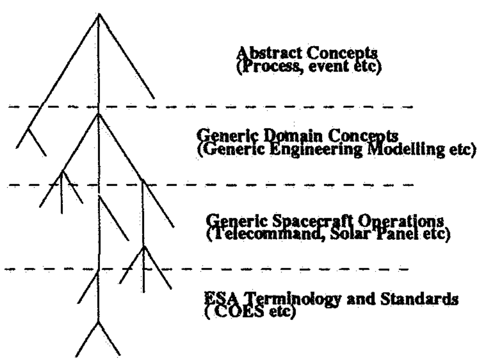

Figure 9 Layers of increasing specialisation in the spacecraft operations ontology

5. A MEDIUM FOR COLLABORATIVE MISSION DESIGN AND OPERATIONS

When the ATOS programme was conceived, four applications were identified as comprising the most promising areas for exploitation of AI technology in a space mission support system. These are: Mission Preparation, Mission Planning, Computer Assisted Operations and Advanced Training. They remain concrete target areas for ATOS application. It is unlikely however that these sub-domains will be realised as discrete components within the ATOS infrastructure. "Cutting" the ontology in this way may well prove to be inefficient. A more natural ontological division, which minimises the need for interaction between applications, may be more appropriate. The ontological analysis being conducted in ATOS-1 may suggest a different partitioning of the domain and may conclude that a larger number of smaller applications would be more appropriate. Unless this matter is addressed, the undisciplined interchange of knowledge between applications could be too unwieldy. One must attempt to minimise the ontological commitments between applications in order to maximise the independence of these applications. This results in minimising the need for cooperation between them. In this way the architecture will be open to the greatest possible extent. Shared ontology should not be viewed as a constraining factor, but as a mechanism to permit the ***integration of disparate views of the domain and of methods for problem solving***. For example, an application which is modelling a device mechanically views the device differently from an application modelling the electronics controlling the mechanical linkages. Both applications however, if they are to cooperate, need to share some aspects of the model. This is where ontology is crucial.

In making the comments above it is important to distinguish between knowledge sharing, which is the placement of knowledge within tools and information bases for direct access by those tools, as contrasted against knowledge communication (as typified by KQML), which is concerned with the dynamic aspects and inter-relationships between knowledge "islands". It is the latter where it is desirable to minimise ontological commitments.

PACT (Ref. 1) points out that "in current infrastructures, applications do not really interact with respect to a shared model: the users do, but the applications do not know this is happening". A group of users working on a mission each have their own tasks, goals and domains, but they nevertheless have a shared view of the evolving mission and spacecraft design. ATOS technology attempts to capture this as knowledge. The evolving mission design, the representation of the spacecraft, its operating procedures and mission objectives, are represented only very superficially in current computer systems, if at all. Ontologies are not represented in any way within current implementations. The basic premise of ATOS is that we can move to a system in which applications themselves interact though a ***shared explicit model of the mission.*** This requires the establishment of a ***knowledge level bus*** into which applications are plugged.

Spacecraft design, mission planning and analysis are "processes of negotiation; decisions are made and changed frequently as specifications change and new implementation ideas proposed. Applications must interact frequently, interchanging relatively complex information. The applications must assist the users in understanding and keeping track of each others constraints, dependencies, limitations and assumptions. Different users may be concerned, at any one instant, with different problems or different aspects of the same problem, or will be working at different levels of detail. Despite these differences in perspective they all share considerable information about the overall mission". Enabling users to share this information and to coordinate the decision making is one of the problems being addressed in ATOS for the domain of spacecraft operations. The role of common ontology is crucial in enabling collaborative space mission design and operations. It is necessary for the applications to agree on many matters, including definitions of space, time, coordinate frames, units of measure, system structure and constraints, in order to effect translation between the different representations used by the applications.

Research has shown that application integration (ie agreement on the form of messages, as opposed to the content of messages), even across heterogeneous platforms, has turned out to be a relatively easy task. However, to enable knowledge sharing one has to tackle the far harder and more fundamental problem of agreeing on ontological commitments. This is due to the differences in abstractions and views employed by the different applications in areas such as planning, diagnosis, design and modelling. The shared language to which applications must adhere, couples these abstractions and ***creates the illusion of a shared MIB model without the constraints and bottlenecks that occur in enforced centralised approaches.*** This more loosely coupled architecture permits currently disjoint user teams to cooperate without the imposition of centralised technologies on existing work patterns, and the inevitable disruption of those work patterns. We view ATOS technology as more fundamentally practical, open and of sounder foundation than any centralised approach could achieve.

6. ATOS ARCHITECTURES

We intend to directly utilise the ontology developed in ATOS-1 in the construction of the architecture, firstly in the creation of the mission information base schema and also in coupling interfaces between ATOS applications. This idea is illustrated in figure 10:

There are three perspectives on how the ontology would be used to construct an ATOS architecture:

1. Translation into the representation schema employed within selected MIB and advanced application technologies.
2. To support the reuse of generic operations knowledge across missions and across application implementation platforms in a form separate from its actual encoding within the MIB. We call this a knowledge resources base (KRB).

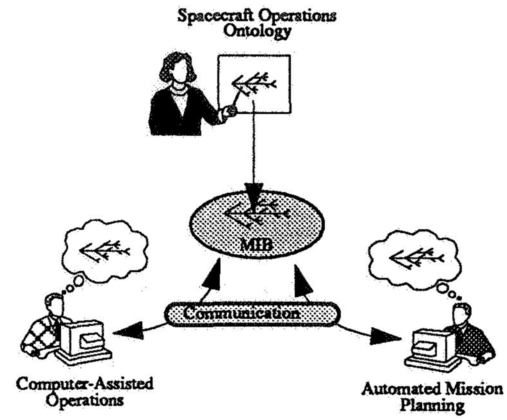

Figure 10 The role of the ontology in the ATOS architecture

3. To develop a set of run-time communications protocols in order to enable different inference engines to reason using the knowledge stored in the MIB, a so-called knowledge query and manipulation language.

6.1 Architectural Perspective 1

Space permits only the first perspective to be described in this paper, which is illustrated in figure 11. The principal elements to consider with respect to this architecture are as follows:

- The common Spacecraft Operations Ontology is maintained as a collection of machine readable definitions in Ontolingua. Ontolingua is itself defined in terms of KIF.
- The common ontology is effectively a reference source of knowledge structures which are deployed into parts of the ATOS system itself. The Ontolingua definitions themselves do not form part of the final system. The ontology is translated (semi) automatically into other parts of the system, so as to establish a common model of the domain throughout ATOS.
- The MIB contents definition is derived by translating the ontology into the MIB information or knowledge model. This is an off-line process and happens only once during the development of an ATOS-based MCS. The MIB's information or knowledge abstraction may be provided directly by a specific commercial tool or layered upon one. In the later case the MIB platform will be selected upon the basis of the flexibility of the storage management it provides rather than the

expressive capability of its data model.

- Advanced application modules (AAMs) will need to share the common ontology in order to "understand" the relevant contents of the MIB. If an AAM is to reason using knowledge stored in the MIB this is also a prerequisite. For example, a planning tool, will need to know whether the MIB calls the results of successfully executing an activity a "postcondition", or an "effect".

  The ontology (or relevant parts of it) will be translated into the KBS tool which is being used for developing the AAM. For example, this would consist of a collection of classes and their associated slots which are equivalent to the Ontolingua classes and relations defined in the ontology.

  The translated ontology provides a set of definitions for the application developer to build his implementation in terms of, for example, in the planner example given above definitions of activity, procedure, temporal constraint would be provided. Application knowledge will be created by instantiating the classes etc derived from the ontology or by extending the definitions with any further knowledge structures which are required specifically to support the task of the AAM.

  As with the MIB, the translation process is off-line and occurs only once during the development of an AAM.

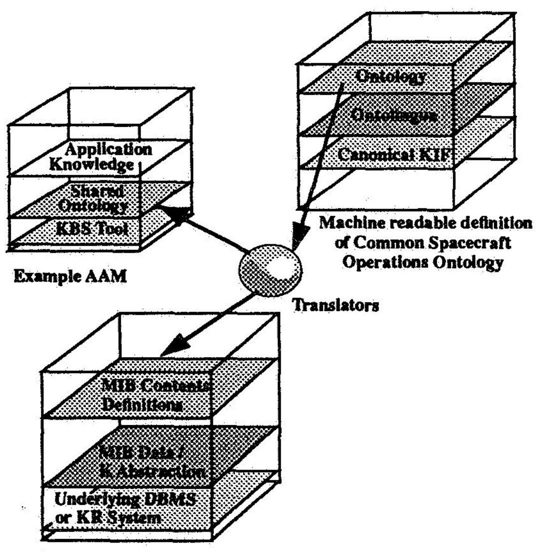

Figure 11 Architectural perspective 1

7. TECHNOLOGICAL FOUNDATIONS OF ATOS

Knowledge sharing, reuse and communication are problems in a wide variety of application domains, not just spacecraft operations. In setting out to address these technological problems within the ATOS programme we have made a conscious effort to follow researchers in other domains and to benefit from fundamental research which is addressing the underlying technical issues.

A particular influence on our technological approach is the work being carried out within the DARPA Knowledge Sharing Effort (Ref. 7). This initiative is working towards the establishment of standards for knowledge interchange (KIF), interoperability between intelligent agents (KQML) and tools to support the development of common ontologies for particular domains (Ontolingua).

With respect to ontology, there are a number of sources of information which are guiding and influencing its development. These are:

- Previous research in knowledge-based applications, in particular those in the areas of planning and scheduling, model-based reasoning and qualitative modelling. In particular, work which has a sound theoretical foundation. Although much of this previous work does not formally define the ontology it is adopting, reusable ontological fragments can be extracted with careful analysis. For examples of such sources, see Ref. 12, 13, 14 and 15.
- On-going research within the DARPA Knowledge Sharing Effort on the development of common ontologies for a number of domains.
- Previous applications in the space domain which serve to identify the domain specific knowledge structures and specialisations which are needed to use the more generic aspects of the ontology in the ATOS applications.
- Work at ESOC in the establishment of standards for ground based spacecraft control systems, and in particular the work of the Committee for Operations and EGSE Standards (COES). For examples see Ref. 16 and 17.

8. POSSIBLE FUTURE DIRECTIONS FOR ATOS

We hope that the core ontology of spacecraft operations, being developed in ATOS-1, will be able to evolve into a concrete standard which will act as a lever to enable the development of a range of advanced mission support and operations applications deployed within an integrated mission control system. The ontology, being expressed using a formal representation explicitly designed for the specification and export of portable ontologies, permits its direct use in the construction of such applications and their knowledge bases. The mechanism for this will be the automatic, or semi-automatic, translation of the ontology into other representation systems employed by these applications. In support of this, the ATOS programme could become the coordinating initiative for the distribution of the ontology and could make available skeletal translation environments to other representation systems. We see the need for the following:

- To establish the means by which the core ontology being developed in ATOS-1 can be further pursued outside of the project, including funded experiments aimed at verifying ontological commitments between planned application domains.

- To establish the means by which the ontology can be transferred, with its translation environment, to parties authorised to utilise the knowledge resources being developed in ATOS-1.

- To establish an advanced interfaces initiative aimed at specifying the standard knowledge bus into which third party applications can be plugged, together with the means to verify the correctness of function of those applications with respect to the ontology. This is similar to that needed for communications protocol verification.

- To establish practical projects, aimed at developing wanted applications (not prototypes), which adhere to the ontology and which concentrate upon identification of minimum ontological commitment between sub-domains.

In particular, we recommend that the continuation of the ATOS programme, in parallel to and beyond ATOS-1, could follow a collaborative model similar to the PACT initiative. We believe it would be quite practical to establish core knowledge bus facilities, operating over a wide area network (eg the InterNet), in order to couple development and research teams working at different sites on different aspects of ATOS technology and its application. The aim would be to bring together other contractors, who have already contributed to furthering the use of AI in space operations in pre-ATOS prototype studies at ESOC, in a way which permits technology transfer and the further coordinated development of the ontology and mission information base.

Recognising the significance of agreement on definitions is the key to moving knowledge based systems off the side lines and into mainstream mission support and operations. The aim is to create a medium in which collaborative mission design and operations can flourish.

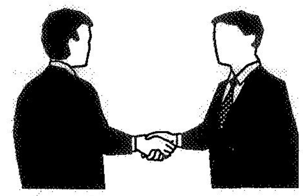

Figure 12 The answer

9. CONTACT DETAILS

The first issue of the Ontology of Spacecraft Operations, which must be considered a "draft proposal", is to be available in July of 1993. Requests for copies of this document should be made to Mr. H A Laue at the European Space Operations Centre, Darmstadt, Germany. We invite comment on the ontology from authorities and contractors across the space industry.

Eventually we also see the need, and will support, the establishment of a forum for common discussion regarding the ontology, the members of which will collaborate on its further development and exploitation. Informal communication can be established now by contacting the authors of this paper at the following email addresses:

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