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Artificial Intelligence: Utilization in Advanced Space Missions

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ABSTRACT

The present report summarizes the research activities of the 1980 NASA "Technology Feasibility" Summer Study. The focus was the development of potential NASA programs designed to optimize the utilization of advanced automation. Within the scope of the study was the definition of advanced space missions, identification of R&D requirements, and a· feasibility assessment.

Mission definitions included an interactive satellite designed to continuously monitor the terrestrial environment; a permanently orbiting space manufacturing facility; a self-replicating lunar factory; and, a fully autonomous interstellar explorer.

Available AI systems were determined to encompass machine intelligence requirements to some degree. However, a major technological gap was noted, that is a machine capacity for effective hypothesis formation and testing.

INTRODUCTION

During the summer of 1980 a NASA sponsored interdisciplinary group met at the University of Santa Clara to discuss the potential uses of advanced automation, specifically artificial intelligence (AI) and robotics, in future space missions. The task of the study group was to 1) define mission objectives requiring advanced machine intelligence and 2) ascertain the feasibility of such missions in light of state of the art AI systems.

Four teams defined mission objectives in individual space utilization areas. A Terrestrial Applications group selected an earth orbiting, interactive satellite designed to continuously monitor the terrestrial environment and its resources. The Space Manufacturing team proposed a permanently orbiting space manufacturing facility which would utilize extra-terrestrial materials. A Self-Replication group organized a projected design for a lunar factory consisting of self-replicating and self-maintaining systems. Finally, a Space Exploration team, in which the author participated proposed a autonomous interstellar explorer, to be first demonstrated within the solar system on Saturn's largest moon, Titan.

Each of the mission objectives will be briefly described, and technology drivers will be emphasized. Common machine intelligence requirements for successful mission achievement will also be pointed out and considered in terms of currently available AI technology.

TERRESTRIAL APPLICATIONS

The Terrestrial Applications teams proposed an Intelligence Earth Sensory Information System (IESSIS). What would make such a system unique (as compared to other NASA applications satellites) is its capacity for goal oriented data gathering, based on requested observations and on previously collected information stored in the form of a self-modifying "world model". Also unique is it's proposed user-oriented interface which would make it possible for the naive user to retrieve useful information from its data base. Such a system would require a flexible natural language capacity for (efficient) human-satellite communication. Finally, the system would require some moderate decision making and abstraction capacity for appropriate deployment of sensor functions and world model construction and updating, respectively. Interacting satellite functions are presented in Figure 1.

SPACE MANUFACTURING

The focus of the Space Manufacturing group was the development of a permanent general purpose, space manufacturing facility (SMF) in Low Earth

Orbit. The purpose of such a facility is the effective processing and utilization of non-terrestrial materials for such projects as solar power stations, communications satellites orbiting and lunar telescopes, etc. Phase I of the mission would include an earth generated raw materials "starting kit" from which space manufactured factory components may derive. A second phase would include an increased dependence on non-terrestrial resources such as the moon and asteroids for provision of manufacturing components. Finally the SMF would be independently responsible for the manufacture of other space utilization equipment as described above. The major technology driver identified in the context of this mission is advanced teleoperation and ultimately autonomous robots.

SELF-REPLICATION

The Self-Replicating Systems Team proposed an automated factory located on the lunar surface consisting of component robots with the capability of creating other systems like themselves. These "offspring" robots and their decendents would also possess the capacity for self-replication. Even more advanced systems of this sort may be capable of adaptation through robot generated "improved" designs determined by changing environmental requirements.

An early stage of self replicating systems presented in Figure 2 involves an earth supplied "parts fin" from which robot copies could be constructed. Later stages (Figure 3) involve automated manufacture of the components necessary for the construction of the offspring.

SPACE EXPLORATION

The mission envisaged by the Space Exploration Team encompassed a continuum of exploratory activity designed to culminate in a fully autonomous exploration of space beyond our solar system. The primary focus was to condense into a single extended mission NASA's current sequential approach of reconnaissance, exploration and intensive study.

In order to maintain linkages with current and opportunity NASA activity and between short and long term objectives on initial Titan demonstration was proposed in which application of current AI technologies could be tested.

A summary statement of mission functions essential to the maintenance of system components and to conducting exploratory investigation are as follows: 1) select interesting problems/sites, 2) plan and sequence mission stages, including deployment strategies for landers and probes, 3) navigate in space and on the ground by planning trajectories and categorizing regions of traversibility, 4) autonomous maintenance of precision pointing, thermal control, and communications links, 5) budget energy requirements of onboard instrumentation, 6) diagnose malfunction, correct detected faults, service, and maintain, 7) determine data-taking tasks, set priorities and sequence and coordinate sensor tasks, 8) control deployment of sensors, 9) handle and analyze samples, 10) selectively organize and reduce data, correlate results from different sensors, and extract information, 11) generate and test hypotheses, and 12) generate and use criteria for discarding or adopting hypotheses with confidence.

TECHNOLOGY DRIVERS FOR ADVANCED SPACE MISSIONS

Mission functions may be summarized in two general categories 1) Mission Integrity, and 2) Model Construction. Both categories impose considerable pressure on current AI technology for development in overlapping areas of machine intelligence. These requirements represent research needs in domains of current concern in the AI community as well as research needs in directions which have not yet been systematically undertaken.

Successful missions at the level of mission integrity would require applications of theoretical AI systems in computer perception and pattern recognition for imaging and low level classification of data. This also presupposes the utilization of a variety of remote and near sensing equipment. On-board processing of collected data would serve to coordinate distributed systems and planning activity in terms of reasoning, action synthesis, and manipulation.

With respect to reasoning, automated decision making emerges as an essential subcomponent deserving the attention of applications research. Within this area development might proceed along the lines of current expert systems, with advancements in interacting simulation models and rule based logic. Some research concerns which depart from current trends were also recognized. These concerns are particularly outstanding in the areas of alternative computer logics and in self-constructing knowledge bases in learning expert systems.

With respect to action synthesis, or procedural sequencing, technology application needs have been identified for representing the relationship between predefined goal states and current state, and for reducing the discrepancy between the two through automated implementation of subgoals and tasks. Such a system implies the utilization of a sequential informational feedback loop. A more difficult problem lies in the domain of simultaneous coordination through anticipation, that is prediction of the most appropriate action patterns through experience and implemation of such action before a large discrepancy occurs.

Complementary to the above capability is the capacity for automated construction of unprogrammed goal states as the result of environmental feedback. These latter two technology drivers fall under the general heading of automated learning and are not part of the current research activities of the AI community.

The last sub-area of technology requirements within the category of mission integrity is manipulation. It is expected that autonomous systems be capable of self-maintenance and repair, as well as of sample collection for data analysis and utilization in decision processes. The former task presupposes some initial ability for self-diagnosis, while both tasks require a variety of effector capabilities for dealing with a wide range of situational demands, from gosss to very refined manipulation. Here advances in robotics with respect to hand-eye coordination and force and propoceptive feedback informational systems emerge as important.

One final technology driver inherent in the above discussion is the capability for automated planning and coordination of the distributed sub-component described. Figure 4 represents the relationship between the technology drivers outlined above.

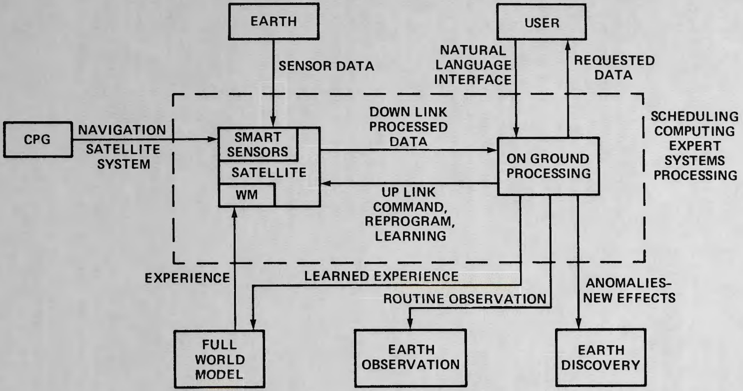
The technology drivers identified for the model construction category of mission functions overlap to some degree with the drivers outlined in mission integrity. Automated intelligence planning is perceived as a general requirement in terms of defining scientific goals (both preprogrammed and self-generated) and for the definition of appropriate subgoals. Advanced decision making is also an essential prerequisite for implementing scientific research and for conducting experiments. Decisions such as whether or not an experiment should be carried out, and where and when it should be conducted, could be accomplished, as for mission integrity, through developments in the application of current theoretical models of expert systems. Reduction of collected sensory information into informal categories is also a significant technology driver. Here a number of requirements emerge. The first is an ability to describe data at the simplest perceptual level. A higher order task is the addition of data descriptions to a knowledge lease for purposes of classification. Classification may be accomplished in terms of given categories of knowledge which requires some low level hypothesis generation and test. A more advanced capacity would be the capability for reorganizing old categories into new schemes or structures as a result of active acquisition of information. Underlying this form of classification activity is again the processes of hypothesis formation and testing. All of the above mentioned tasks require varying levels of applications research and development in order to transform them into freely realized capabilities.

Finally, a requirement exists within the area of communication, that is the reporting of acquired information to human users. This capability also requires reduction but in a different form. Here the emphasis is on an automated selection process, one in which an advanced decision system decides what acquired knowledge and what interesting hypotheses are appropriate to report. In addition to decision capabilities, this area underscores the need for development in Natural Language Interface. Figure 5 represents the relationship of technology requirements for the Scientific investigation aspect of Space Exploration missions.

SUMMARY

Potential NASA missions were defined and described in four areas. Machine intelligence requirements for mission success were summarized and included advanced remote sensing, and imaging techniques, pattern recognition, deductive and inductive logic for decision making, and learning (broadly defined as the capacity to modify output as the result of environmental or internal feedback). State of the Art AI systems were reviewed and determined to encompass all of these processes to some degree. A higher order intelligence requirement, identified as hypotheses formation, or the capacity to form universals associated with patterns present in the environment, presented itself however as a major technological gap between currently available techniques and advanced mission requirements. Other areas of technology feasibility assessment included "world model" based information systems, a natural language man/machine communication interface, and the development of sophisticated teleoperators and robots.

FIGURE 1: AN INTELLIGENT SATELLITE WITH EXPERIENCE, CAPABLE OF ADDITIONAL LEARNING AND DISCOVERY



SATELLITE SYSTEM PROCESSES DATA TO PRODUCE:

1. ROUTINE OBSERVATIONS FOR FURTHER ANALYSIS
2. GOAL ORIENTED OBSERVATIONS IN USER FORM
3. DISCOVERY OF NEW EFFECTS BY ANOMALIES

FIGURE 2: A SIMPLE SELF-REPLICATING SYSTEM

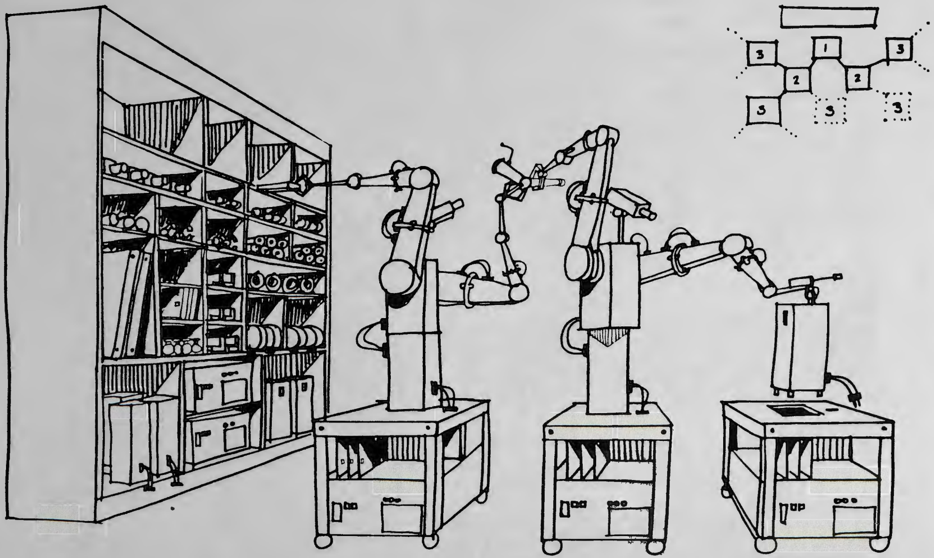


FIGURE 3:

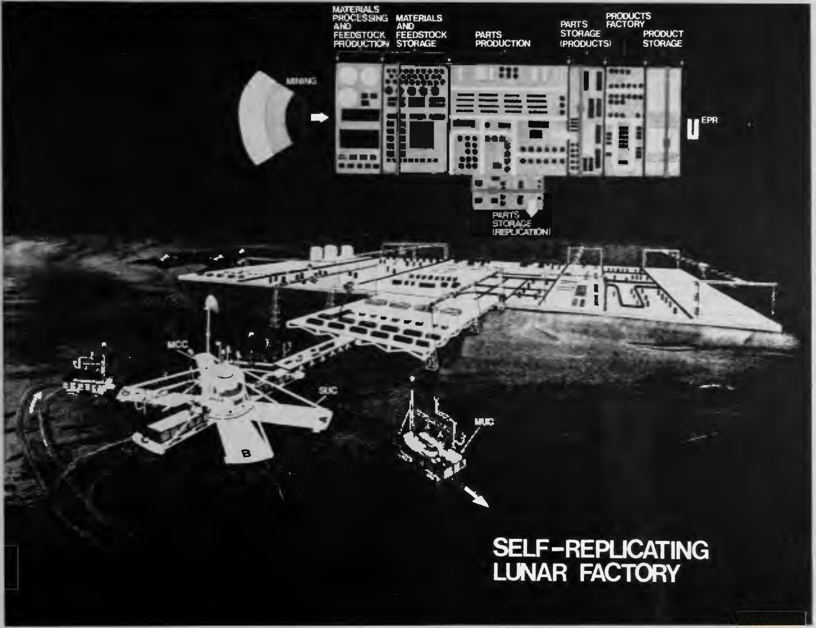

MATERIALS PROCESSING AND FEEDSTOCK PRODUCTION
MATERIALS AND FEEDSTOCK STORAGE
PARTS PRODUCTION
PARTS STORAGE (PRODUCTS)
PRODUCTS FACTORY
PRODUCT STORAGE
MINING
EPR
PARTS STORAGE (REPLICATION)
MCC
SUC
MUC
B
SELF-REPLICATING LUNAR FACTORY

FIGURE 4: SYSTEMS REQUIREMENTS FOR MAINTENANCE OF MISSION INTEGRITY

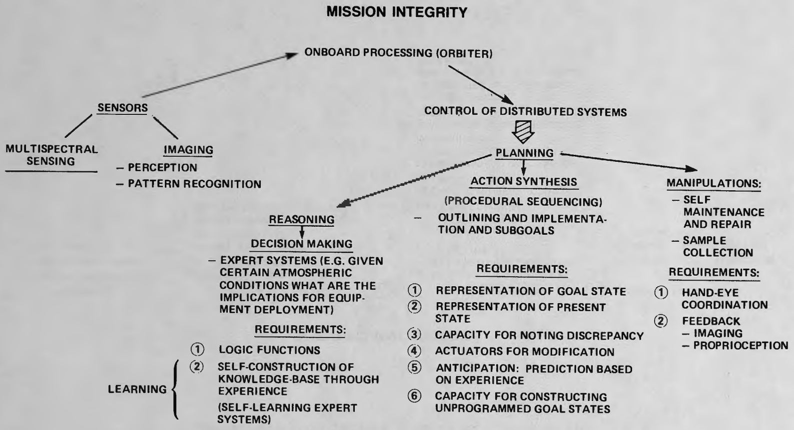


FIGURE 5: ROBOTIC FUNCTIONS IN WORLD MODEL CONSTRUCTION

SCIENTIFIC INVESTIGATION

PLANNING ⇒ **DECISION MAKING** ⇒ **DATA PROCESSING** ⇒ **COMMUNICATION OF RESULTS**

PLANNING

ACTION SYNTHESIS

- PROGRAMMED GOALS
- SELF-DIRECTED

DECISION MAKING

- WHETHER OR NOT TO CONDUCT EXPERIMENTS
- WHERE, EXPERIMENTS SHOULD BE CARRIED OUT
- USE OF APPROPRIATE SENSORS AND EXPERIMENTAL APPARATUS

DATA PROCESSING

- REDUCTION OF SENSORY DATA INTO INFORMATION CATEGORIES

REQUIREMENTS:

1. DATA DESCRIPTION
2. ADDING NEW DESCRIPTIONS TO KNOWLEDGE BASE
3. CLASSIFICATION IN TERMS OF GIVEN CATEGORIES OF KNOWLEDGE
4. HYPOTHESIS GENERATION AND TESTING
5. REORGANIZATION OF OLD CATEGORIES INTO NEW ONES WHEN THE OLD ARE NO LONGER SUFFICIENT

COMMUNICATION OF RESULTS

- INFORMATION REDUCTION
- REPORT OF INTERESTING FINDINGS