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# HABITAT AUTOMATION

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## ABSTRACT

**A habitat, on either the surface of the Moon or Mars, will be designed and built with the proven technologies of that day. These technologies will be mature and readily available to the habitat designer. We believe an acceleration of the normal pace of automation would allow a habitat to be safer and more easily maintained than would be the case otherwise. This document examines the operation of a habitat and describes elements of that operation which may benefit from an increased use of automation. Research topics within the automation realm are then defined and discussed with respect to the role they can have in the design of the habitat. Problems associated with the integration of advanced technologies into real-world projects at NASA are also addressed.**

## INTRODUCTION

A habitat, on either the surface of the Moon or Mars, will be designed and built with the proven technologies of that day. These technologies will be mature and readily available to the habitat designer. We believe an acceleration of the normal pace of automation would allow a habitat to be safer and more easily maintained than would be the case otherwise. Because only mature technologies will be useful to habitat designers, it is necessary to assess the current maturity of automation. "Automation", as used in this document, refers primarily to the advanced software control of a complex array of equipment and sensors, and secondarily to the isolated operation of an autonomous robot. A "habitat" is defined to be the shirt-sleeved living and working quarters of a crew in a hostile space-based environment. The specific habitat under consideration is that defined as Option 5A in the *Habitation and Human Systems Addendum* [1] to the *Report of the 90-Day Study on Human Exploration of the Moon and Mars* [2]. This paper examines the operation of a habitat and describes elements of that operation which may benefit from an increased use of automation. These elements include fault-tolerance, graceful degradation, localization of failures, human-machine interaction, non-invasive repair strategies, and some logistics matters. Some research topics within the automation realm are then defined and discussed with respect to the role they can have in the design of the habitat. These topics include fault-diagnosis and recovery methods, planning, and speech-recognition. The research topics are discussed only with reference to their potential application to the habitat design. More detailed sources of information on specific topics are at times suggested.

## LOGISTICS

Logistics involves the design, operational planning, and provisioning for the habitat. Logistics has historically taken a back seat to most other disciplines during development projects. In the creation of a remote space-based habitat, however, we can ill afford to have it remain there. Many details need to be decided upon in creating a viable logistics support plan for a space habitat. One of the largest decisions involves the placement of the depot facility. Having a depot facility co-located with the habitat may prove to be a necessity due to the great number of line replaceable units (LRUs) that would otherwise have to be present at the site. Co-locating a depot-level repair facility with the habitat, however, will be a unique undertaking. In the US armed forces, for the support of millions of pieces of electronic equipment, there exist a handful of depot level repair facilities. The habitat depot will, however, fulfill a much more exclusive support role than a general purpose depot.

Regardless of depot placement, the difficulty in maintaining logistics support for the habitat will be great. Logistics support for Operation Desert Storm has been a topic of conversation in recent months. The inability to get the proper supplies to our armed forces in the Persian Gulf could have resulted in unnecessary loss of life. Our inability to get the proper supplies to a space habitat could do likewise. Whatever logistics plan we decide on will have to accommodate complex, risky, and inherently unreliable resupply missions.

It is important to design the subsystems of the habitat to capitalize on commonality. Having different subsystems with interchangeable LRUs, if possible, would add depth and flexibility to system maintenance. An overriding concern of this design process will be to keep unique parts counts at a minimum. This will reduce the cost of initially outfitting the habitat's repair facilities and reduce the ongoing life cycle costs associated with resupply. Perhaps a logistics "Tiger Team" could be assembled whose purpose would be to minimize the number of unique components incorporated into the subsystem designs, as well as to minimize the support items required to maintain the subsystems. Without such an influence it is far too easy for subsystem designers to use either what is available to them or what they are most comfortable with.

## DESIGN

Each of the subsystems of the habitat will be integral in sustaining life. This will require constant availability of each of the subsystems. The ultimate design goal of a continuously operating system is for no one failure to incapacitate or degrade system performance. An equally laudable repair goal is for no one repair to require a suspension of, or degradation of, system performance. Fault tolerant system operation, graceful system degradation, and non-invasive repair strategies will be necessary elements of the design of the habitat.

Constant availability implies the presence of fault redundant operation (to ensure stable operation of habitat functions); localization of failures (to prevent cascading effect of failures); subsystem isolation (to prevent cascading effect of failures between subsystems); and an adequate logistics pipeline (to allow for repair of faulty equipment in a timely manner). In a terrestrial factory this presents a difficult, but doable task. On the Moon or Mars it will be much more difficult, with the consequences of failure being much more grave.

### Fault Redundancy

Fault redundancy usually takes the form of hot and cold spares and, in some cases, entire backup subsystems. Perhaps some redundancy of this form may be necessary, but an extremely high cost would be paid for it. The cost for launching a metric ton of cargo into orbit is extremely high; and this apart from placement of the cargo on the surface of the Moon or Mars. Because of the conflict between the need for redundancy and its high cost, an analysis is needed to determine the most cost-effective forms of redundancy to employ in the design of the habitat.

### Subsystem Commonality

The subsystems, while varying greatly in their duties and designs, provide an opportunity for exploitation of their common features. Each subsystem will be required to 1) plan and control it's own operations; 2) determine it's own ability or inability to function; 3) cooperate with other subsystems as necessary; and 4) communicate with a system level executive as necessary. These points can be restated as 1) planning and scheduling; 2) fault detection, isolation and recovery (FDIR); 3) interfacing; and 4) hierarchical communication and control. Planners and schedulers, unique to each subsystem, should be able to communicate with one another with ease in that they will be required to operate on similar types of objects. Fault diagnostic programs should operate on similar principles so as to benefit one another during their operation. The philosophy behind subsystem interfaces should be defined early and adhered to strictly during the design of the habitat. Subsystem interfaces should be thought of as part of the system and *designed in* as opposed to being patched in when found necessary. Design documents should be created which encourage and enforce design commonality and consistency in subsystem interfacing. These principles, applied correctly, should result in cooperation of the subsystems at the system level.

**Physical Dispersion of Subsystems**

While we want the subsystems to use common parts and to be built with similar design paradigms, they will also have to remain electronically isolated from one another to prevent the possibility of failures leaping across subsystems. To minimize the potential hazardous effects physical phenomena, such as fire or flooding, may have on the equipment, the subsystems themselves should also be distributed over a large physical area.

**Importance of System "State" Maintenance**

Repair strategies must be developed that take into account the state of the equipment and potential loss of state information via failures. "State" refers to the sum of the many facts which together define a point in time in the life of the habitat. It is important that this abstract state represent the true state of the habitat environment as best it can. A sophisticated network of sensors of all types will help us to maintain this state validity. This abstract state will then be used by the various health monitoring systems and fault detection programs to assist in the determination of proper equipment and subsystem operation. It provides a model of the habitat with which the various subsystems can reason. Reasoning upon this abstract state is known as Model-Based Reasoning (MBR).

Each of the subsystems will have different levels of automated response, implemented at the hardware level, to ensure the security of both equipment and personnel. In design terminology, this lowest level of automated response to the detection of hardware faults, is known as *safing the system*. The impact of safing will first be felt, via the sensors, by a system executive. (We use the term Habitat or Space Habitat Executive (HE/SHE). HE will be used for consistency). The system state will then be assessed and recovery procedures, appropriate to the situation, implemented. Perhaps HE could be sent a "heads-up" message just prior to a subsystem safing itself. In this way the strategy used in resuming operation could have been designed beforehand and thus resumption of processing could proceed in a more studied fashion.

This implies a tight coupling of the hardware and software. This tight coupling can only exist if it has been designed into the system. To accommodate this we should ensure a tight communication exists between the hardware and software developers during the design stages. A lack of communication would lead to complication of the software designs and a reduction in the efficacy of the software in handling unusual states.

**Human-Machine Interaction**

Input/Output (I/O) in the habitat will take many and varied forms. Traditional computer input via the keyboard and output via the computer screen will be assisted by speech recognition systems and natural language understanding capabilities; visual control, possibly with the aid of head gear such as is used in virtual reality testbeds; hearing, via our ability to distinguish variations in tones, as well as the location in three-dimensional space of the source of said tones.

It should prove beneficial that the computer react to the voice of the habitat occupants. Voice input will allow a tangential task to be started while not disrupting the primary task to which the speaker is employed. A driving principle behind the development of the habitat's voice and data control systems, should be the desire to not enslave the habitat occupants to use of a stringent syntax. Stringent enforcement should be needed only when commands are ambiguous or nonsensical.

Visual "heads up" displays, such as are now used in jet cockpits, and flat wall displays and touch screens can be used to free the habitat occupants from the need to sit in front of small computer screens. Virtual reality helmets can be used daily to simplify the control of robots outside of the habitat.

We have only begun to explore the concept of using hearing in human machine interaction. The auditory sense can provide an alternate route for critical information in complex environments during periods in which the user's visual capacity is already greatly taxed. "Ames is currently investigating the underlying perceptual principles of auditory displays and is also developing a prototype signal processor based on these principles. Rather than use a spherical array of speakers, the prototype maximizes portability by synthetically generating 3-D sound cues in real-time for delivery through earphones. Unlike conventional stereo, sources will be perceived outside the head at discrete distances and directions from the listener. This is made possible by numerically modelling the effects of the outer ears on the sounds perceived at various spatial locations." [3] These discoveries, and the discoveries of other related programs, are rapidly expanding the role of hearing in the design of future man-machine systems.

The occupants of the habitat should be considered the equivalent of jet aircraft pilots for the purposes of habitat design. This is because, like jet aircraft pilots, they will be hard-pressed during critical events to absorb all of the information available to them. This is especially true if we do not attempt to better distribute the sensory load over all of the senses. Because of this similarity we should assess the state of aircraft cockpit design. Advances in the area of jet aircraft human-machine interaction should be given serious consideration in the design of the habitat. Ames Research Center is now preparing a document which addresses the rationale and philosophy of human-centered aircraft automation. It will address the issues posed by aircraft automation as it has evolved over the past sixty years [4].

Having multiple forms of I/O also provides an inherent redundancy and flexibility in day to day operational use and control of the habitat. When one form of control is incapacitated, for whatever reason, the chances would be much greater that another I/O route exists to fulfill a requirement.

## OPERATION

The subsystems of the habitat will interact constantly. In large systems, subsystem interaction is often handled on an individual basis, with interfaces between subsystems being defined as needed. Within the habitat we will need to constrain subsystem interactions to isolate them from one another. This isolation will allow for 1) the independent development of FDIR programs for each subsystem; 2) the development of a system-wide health monitoring and fault diagnostic program; and 3) the isolation of failure effects to the subsystem in which the failure occurs.

An example of the need to coordinate the activity of subsystems is exemplified by the direct correlation between the consumption of power and the generation of heat. The load placed on a thermal cooling system is driven by the generation of heat which is a side-effect of power usage. As power usage increases the need for thermal cooling increases. When, however, thermal cooling capacity is diminished in some way it may be necessary to reduce the generation of heat, which can only be done by eliminating non-essential power usage. It is the automation of such subsystem interactions that would help simplify the lives of the habitat occupants.

Sensors will maintain a constant flow of real-time information to the individual subsystems of the habitat as well as to HE. HE will resolve the conflicts between subsystems' individual plans and schedules in accordance with a greater awareness of the proper subsystem roles in the habitat. This arbitration between subsystems is not intended to layer a bureaucracy on the running of the habitat. Having HE arbiter all subsystem interaction would produce an unacceptable bottleneck in operation and would increase the damage potential of single point failures. It's role here would be strictly that of resolving subsystem conflicts.

Another aspect of the role of HE involves the scheduled interaction of humans with equipment. Almost all human activity impacts equipment resources in some way. HE will be responsible for the control and sharing of these system resources.

## MAINTENANCE

With manpower being the most precious resource of the habitat, both morally and financially (some figures place the hourly cost of having astronauts in orbit at $35,000 [5]), we must design the subsystems of the habitat to function as autonomously as is practicable.

The normal operation, detection and diagnosis of faults, and repair of subsystems, should be automated to the greatest extent possible. Subsystem health monitoring should allow for automated recognition of, and rerouting of subsystem operation around, minor faults without impacting system operation. Health monitoring should also provide automated diagnosis of minor faults which do impact subsystem operation as quickly as possible. Defective LRUs will be replaced by human repairmen and either disposed of or forwarded to the depot for repair. Over time, perhaps automated subsystem assistants can help with LRU replacement and disposition.

### Robotic Depot Repair Facility

An automated depot-level repair facility is being considered for the habitat. This could be realized by developing a highly automated facility for the repair of all repairable LRUs. Automated component-level equipment repair can be facilitated by such things as 1) human staging and previewing of LRUs; 2) Optical Character Recognition (OCR) coding of all LRUs and replacement part storage locations; 3) recording of all LRU component placements; and 4) a highly constrained environment within which the robot can perform the repairs. This repair strategy will require extensive development and may need to be phased in at an operational habitat.

### Active and Passive Maintenance

System maintenance will have a passive and an active element. The passive element can be thought of as a health monitoring system. The role of this system is to minimize the number of malfunctions requiring immediate operator attention. The system should be capable of handling the great majority of malfunctions, thus allowing the habitat occupants to perform other, more critical tasks. It incorporates 1) trend analysis which can lead to preventive maintenance tasks being assigned to prevent future failures; 2) automatic reconfiguration of system elements to bypass suspected failed LRUs; 3) control of fusion of sensors and static data displays to keep the habitat occupants informed of system status; and 4) interactive data displays to inform the more inquisitive user of the state of the habitat.

Active maintenance will be in the form of FDIR programs, unique to each subsystem, capable of fault-isolation to the LRU level. The FDIR programs will be developed independent of one another but with a common design methodology to allow for communication in the larger system-wide FDIR program. The subsystem FDIR programs will communicate with one another via a blackboard data architecture, controlled by HE, allowing them to share information vital to one another. Using a knowledge-based systems approach, the same inference engine design for each of the subsystems can be used while allowing the data unique to each subsystem to determine the troubleshooting path. This will facilitate a more tractable validation and verification of the various FDIR programs and help simplify the development of a system-wide FDIR program.

The transition from passive to active maintenance will at times take the form of responses to status updates (in the case of non-critical failures) or responses to alarms (in the case of critical failures). HE will be fed information from each of the subsystems at specified time intervals, as well as asynchronously in the event of anomaly detection or user interaction.

## APPLICATION OF AUTOMATION

Candidates for automation, of either form defined earlier, are those tasks which are 1) time consuming; 2) repetitive; 3) uninteresting; 4) well-defined and highly constrainable; and/or 5) operate in isolation. This is not a definitive list in determining what to automate, but does serve as general guidance when considering candidates for automation.

Automation candidates already mentioned include the health monitoring system, HE, the FDIR programs, planners and schedulers unique to each subsystem, and the robotic depot repair facility. Other tasks, which might lend themselves at least partially to automation, are "household chores", such as, food preparation and cleanup, vacuuming and dusting, storage and access of work area tools, inventory control and replenishment, waste disposal, and bathroom cleaning.

As the habitat is to be manned continuously, a means of locally producing fresh vegetable produce will be necessary. A "salad machine", that will provide a variety of fresh vegetables for astronauts on long voyages, is now operational at NASA Ames. [6] The near-term goal is to provide astronauts of Space Station Freedom with fresh salads. The machine may also provide a beneficial side-effect in improving the morale of the crew by offering them a creative outlet during their free time, such as is provided by tending a garden on Earth.

Many opportunities exist for the inclusion of automation in a space habitat. A "a day in the life of the habitat" scenario, developed early on in the project, would provide a model upon which automation concepts could be modeled and thus compared against their more traditional counterparts. The model would also provide an environment within which the interaction of tasks effected by automation could be assessed.

## RESEARCH

The following research topics have been referenced previously in the text. Appearing here is a brief description of their current capabilities and their weaknesses with respect to our application of them in design of a habitat.

### Speech Recognition

Speech recognition is the capacity for a computer to "hear" and correctly identify the spoken word. "Few applications of speech-recognition technology have reached beyond simple, speaker-dependent, isolated-word recognizers with vocabularies of a dozen to a hundred words. Small vocabularies and poor accuracy have limited the applications suitable for speaker-independent systems." [7] Though this was stated over four years ago, and much progress has been made since that time, the more successful systems still recognize only isolated words or short phrases, and require "training" to recognize each speaker's voice. There is also usually no "understanding" of the words spoken (although it can be argued that this is an extension to the concept of speech recognition). The words are usually used only as dumb commands, without semantic significance, in the execution of predefined actions. Further research needs to be performed to improve upon speech recognition in the areas of continuous-speech, speaker-independence, vocabulary size, and accuracy. SRI International has been working on a continuous-speech, speaker-independent, 20,000 word speech recognition system for DARPA. [8] This system, when completed, should be evaluated with respect to its potential usefulness in the habitat.

### Natural Language

Natural language can also be thought of as *speech understanding*. Speech recognition identifies the words, but natural language understanding attempts to derive meaning from the words. This meaning is needed, on the computer side, to "understand" what it is being commanded to do. In addition, the computer needs to be capable of generating semantically correct replies for the user. Natural language is now advertised to be resident in many newly released software products. The natural language referred to is usually nothing much more than lazy syntax enforcement in combination with COBOL-like command statements. While this is in itself a useful software concept, it is not what we have defined here as natural language understanding. To be useful in the operation of the habitat, much more research in natural language understanding needs to be done. At this stage we may be better served by integration of the current, more popular, meaning of natural language.

### Model-based Reasoning (MBR)

"Model-based reasoning uses an internal symbolic model of the system of interest and updates the state of this model based on sensor evidence and cause/effect analysis." [9] MBR has several advantages over other forms of fault diagnostic systems. It can handle systems too large for traditional troubleshooting procedures developed in conjunction with a Failure Modes and Effects Analysis (FMEA). It can also lead to the discovery of faults other than those for which it has been proven to work. "The model-based capabilities of TEXSYS were shown to be advantageous, particularly for detection of unforeseen faults and sensor failures." [10] It may also require less of a knowledge engineering effort, as the model is based more upon device behavior and less upon heuristics unique to the domain. MBR has its drawbacks, however, one of which is excessive use of processor time, as shown in the following excerpt. "It was necessary to rely on a classification or rule-based approach to interpret conflicts in the expert system's model, given the slowness of structural *(model-based)* reasoning." [10] Another weakness of the MBR approach is the time lag which exists in updating the model to reflect what has happened in reality. Often, during times of increased activity, valid states are interpreted as error states due to the model having been inconsistent, for perhaps only a moment, at the time that the data were sampled. Research in MBR needs to focus on how to better represent the actual state expected in the model and how to reason in more general, domain independent ways.

**Planning**

"Any intelligent system that operates in a moderately complex or unpredictable environment must be reactive, that is, it must respond dynamically to changes in its environment." [9] Planning is one activity which we hope to have migrate to the computer in great part due to its time-consuming nature. If done manually, in the habitat, little time would be left for other activities. The current state of planners, however, does not support the depth and flexibility required of the planners in the habitat. Planners are incapable of working on general problems and may continue to be for some time. Successful planners sometimes work only within oversimplified domains or are very domain specific. Planning in the midst of a dynamic domain also changes the content of the plan continually, often invalidating it before it is complete. Much more basic research in planning in a dynamic domain needs to be performed. Perhaps, for habitat needs, research should focus on human assisted planning in addition to the more popular autonomous planning. Some excellent suggestions on space-based planning have been made in Reference 5 (pages 4-8 thru 4-10).

## CONCLUSIONS

The following quotations are all taken from a MITRE Report entitled, *Space Station Freedom Program Advanced Automation: Volume I* [11] and are referenced here without additional comment.

"The research community can be characterized as Ptolemaic: advanced automation is the center of their universe, the rest of the universe orbits around this center." *page 6*

"A Copernican view of advanced automation is required if these technologies are to be used within operational applications." *page 7*

*"...the technology used for Apollo and Shuttle was successful and should be good enough..." page 8*

"Too much innovation causes disruption, while excess stability creates stagnation. There is currently no environments for transitioning innovative technologies and applications into the stable production environments." *page 11*

"... there is a distinct gap that must be filled between the relatively unconstrained environments of the test beds and the constrained production facilities and operations environments." *page 14*

**Suggestions for Future Consideration**

Throughout this paper questions have been raised and further studies have been suggested. To again highlight them they appear here in bullet form.

• To assist in incorporating automation into the operation of the habitat, we must make the habitat designers aware of the areas which may benefit from automation.

• An analysis is necessary to determine the most cost-effective form of redundancy to be employed in the design of the habitat.

• Perhaps a logistics "Tiger Team" could be assembled for the purpose of maximizing commonality and minimizing the number of unique components incorporated into the subsystem designs.

• The location of the depot repair facility will provide the foundation for making many future habitat design decisions.

• Subsystem interfaces should be *designed in* and not developed ad hoc.

• Planners, schedulers, and FDIR programs, unique to each subsystem, should use common data structures to ease system communication.

• Habitat hardware design should consider the effect *safing* will have on HE.

• Having I/O take varied forms will provide an inherent redundancy in the day to day operational use and control of the habitat.

• To assist in the assessment of automation scenarios perhaps a "day in the life of the habitat" model could be developed.

• Perhaps NASA could address the lack of suitable environments for the transitioning of innovative technologies and applications into stable production environments.

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