AN ADAPTABLE PRODUCT FOR MATERIAL PROCESSING AND LIFE SCIENCE MISSIONS

Gregory Wassick and Michael Dobbs
Advanced Modular Power Systems, Inc.
Ann Arbor, Michigan

ABSTRACT

The Experiment Control System II (ECS-II®) is designed to make available to the microgravity research community the same tools and mode of automated experimentation that their ground-based counterparts have enjoyed for the last two decades. The design goal was accomplished by combining commercial automation tools familiar to the experimenter community with system control components that interface with the on-orbit platform in a distributed architecture. The architecture insulates the experimenter from the details of the on-orbit platform while providing the payload engineer with the tools necessary for managing a payload. By using commercial software and hardware components whenever possible, development costs were greatly reduced when compared to traditional space development projects. Using commercial-off-the-shelf (COTS) components also improved the usability of the system by providing familiar user interfaces, providing a wealth of readily available documentation, and reducing the need for training on system-specific details. The modularity of the distributed architecture makes it very amenable for modification to different on-orbit experiments requiring robotics-based automation.

INTRODUCTION

Advanced Modular Power Systems, Inc. (AMPS), a small business, was incorporated in 1990 to conduct R&D and product development of advanced, efficient, cost-effective and reliable energy conversion systems for the production of electrical power in space and terrestrial applications. Similarly, the Space Resources Division(AMPS-SR) concentrates on the research, development, integration and manufacturing of cost-effective instruments, experiments, and complete systems(payloads) for terrestrial markets and space missions.

AMPS-SR objectives are the creation of a space automation supplier to industry. This industry is defined to include suppliers of laboratory automation equipment such as sample preparation and manipulation, sensors, process control, data acquisition and control, and data analysis systems. Technological and economic elements of these industries are well established, with suppliers providing automation-related products and services to terrestrial "customer" industries including electronic, pharmaceutical, chemical, and other consumer product areas (i.e., food and beverage). Many of these same industries, particularly those in the electronic and pharmaceutical areas, also have an active research and development (R&D) interest in the unique properties of the space environment (microgravity, ultrahigh vacuum, view of earth, etc.).

Recognizing the commercial potential of space-based experimentation and discovery as well as manufacturing, AMPS-SR is involved in several joint project activities with both public and private partners. While these projects focus on different niches, they all have a common goal to reduce the cost of space-based research and manufacturing through the development and deployment of technology that extends established terrestrial laboratory automation techniques to the space environment.

This paper examines the system architecture of the Experiment Control System (ECS), as used in the Robot Operated Materials Processing System (ROMPS), and its evolution into the private sector product the ECS-II, which will be used on Wake Shield Facility 3rd flight (WSF-3) as the control system for the Automated Wafer Cartridge System (AWCS). The ECS and ECS-II systems are built around two commercial off-the-shelf (COTS) technologies, Zymark's Zymate System V Controller and Interface and Control Systems' (ICS) Spacecraft Command Language (SCL).

Other ECS-2 missions include, the enhanced ROMPS-2, the large scale manufacturing mission on WSF-4, and a joint JPL-AMPS INSTEP payload that will demonstrate essential AMTEC power conversion technology for the Pluto Express program.

ROMPS MISSION OVERVIEW

In 1991 a request was made by NASA's Goddard Space Flight Center (GSFC) to propose an alternative Experiment Control System (ECS) design for the ROMPS project. The ROMPS project is a Space Shuttle Hitchhiker mission centered around the rapid thermal processing (RTP) of semiconductor materials. The ROMPS mission's short-term objective is to develop commercially promising in-space processes by using a robot-based automation system to lower the cost of the material procedures. Figure 1 shows the payload configuration of the ROMPS Hitchhiker payload.

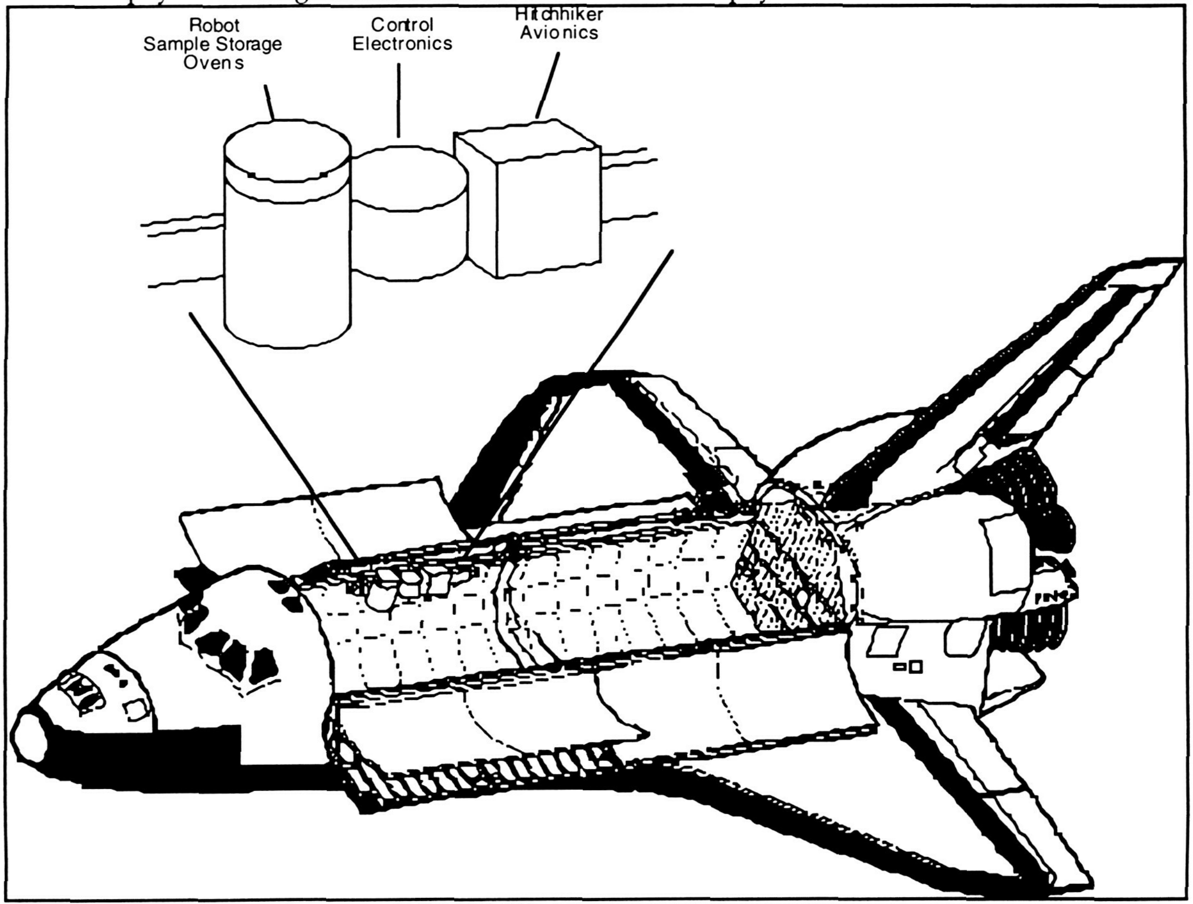


Figure 1. ROMPS Hitchhiker Payload Configuration

ROMPS AUTOMATED RAPID THERMAL PROCESSING

Rapid thermal processing is a widely used industrial material processing procedure for two-dimensional semiconductor materials. In this process, a heat source capable of producing uniform surface area temperatures (usually a quartz halogen lamp) is used to melt semiconductor materials. The semiconductor materials are then allowed to cool and recrystallize. Semiconductor materials recrystallized in micro-gravity have larger and more uniform crystals that have better electrical properties.

ROMPS provides a robotic-based system capable of automating the RTP with up to 155 samples. In this system, a custom-built halogen lamp furnace provides the heat source for the RTP of the samples.

A robot designed by GSFC moves the semiconductor samples between their storage racks and the furnace. The ECS was developed to provide the computer, computer software, and electrical subsystems for automatically controlling and monitoring the RTP of the semiconductor materials.

WSF-3/AWCS MISSION OVERVIEW

Carried into space in the payload bay of the Space Shuttle, the Wake Shield Facility (WSF) presents a unique platform for the development of advanced semiconductor materials and devices through the use of the ultra-vacuum of space. The WSF is released into orbit by the Shuttle RMS robot arm. After the WSF maneuvers away from the Shuttle, it orients itself to shield out the residual atmosphere that remains in low earth orbit, thereby creating an ultra-pure vacuum in its wake, see Figure 2.

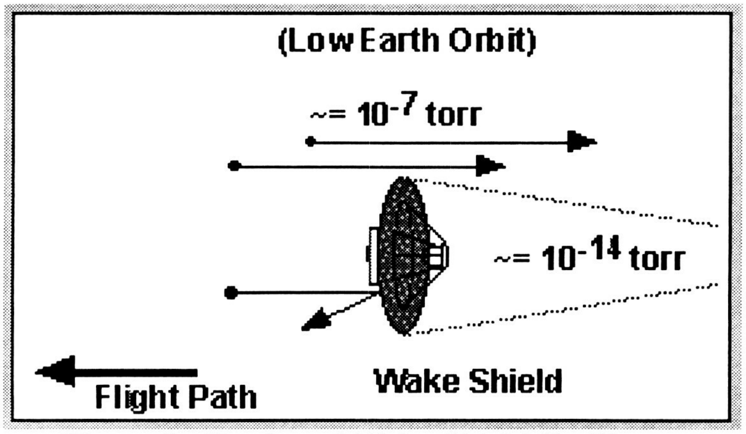


Figure 2 - Deployed Wake Shield Facility

This ultra-vacuum, nearly empty of all molecules, is then used to conduct a series of thin film growths by a process called molecular beam epitaxy (MBE) which produces exceptionally pure and atomically ordered thin films of semiconductor compounds such as gallium arsenide. Using this process, the WSF offers the potential of producing the next generation of semiconductor and superconductor thin film materials, and the devices they will make possible. After a several day period of free flight, the WSF platform is retrieved by the Space Shuttle and returned to Earth.

The first AWCS was designed to provide the WSF with a prototype manufacturing facility. In its current configuration , it will transport 100+ wafers to and from orbit, an increase of 15 times the present number of wafers processed. The AWCS design is readily scaleable to 1000+ wafers required by the WSF-4 mission. The AWCS utilizes a unique, patented 2 degree-of-freedom(dof) robot arm/gripper to move the wafers from the storage racks to the substrate rotator. The present system is designed to mount directly to the existing WSF carousel flange and to conform to ultra-high vacuum (UHV) practices regarding materials and mechanical systems.

WSF-3/AWCS MBE PROCESSING

Epitaxy, a technique for controlled deposition of thin films in a vacuum, is the atomically ordered growth of a material on a substrate in an atom-by-atom, atomic-layer-by-atomic-layer manner. SVEC employs an epitaxial technique known as molecular beam epitaxy (MBE), whereby atoms or molecules emitted from heated crucibles impinge upon a substrate, condensing and forming a thin film, see Figure 3. The better the vacuum

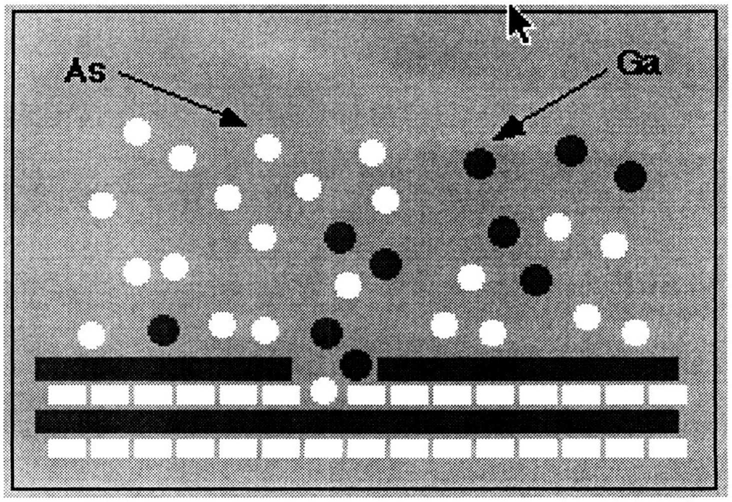


Figure 3 - MBE Processing

quality, the higher the quality of the thin film material grown. Scientists consider this technique to be one of the most powerful methods for synthesizing new and improved materials and devices.

MISSION REQUIREMENTS

Table 1-Mission Requirements Matrix, provides a matrix of the mission requirements for both the ROMPS and WSF-3/AWCS missions. Also, included are the requirements for other upcoming missions.

TABLE 1 - MISSION REQUIREMENTS MATRIX

FUNCTIONAL REQUIREMENTS	ROMPS	WSF-3	ROMPS-2	WSF-4	AMTEC
Robot Requirements					
Motion Control Of N-Dof Robot Mechanisms	4	2	4	2	
End-Of-Travel (Eot) And Over-Force (Ovf)	X	X	X	X	
Calibration Of Home Position	X	X	X	X	
Stored Robot Move Sequences	X	X	X	X	
Processing					
Furnace Controller	X		X	X	
Power Or Temperature Setpoint	X		X	X	
Timed On/Off Sequences	X		X	X	
Multi-Step Time-Temperature Profiles	X		X	X	
Process Sensors					
Thermocouples, Thermistors	X	X	X	X	X
Video-Microscopy			X		
Non-Contact Temperature Measurement			X	X	
Reflected High Energy Electron Diffraction				X	
Process Control					
Closed Loop Temperature Control			X	X	X
Machine Vision Inspection Of Crystal Grain Boundaries			X	X	
Payload Controller					
Science/Engineering Data Collection And Transmission	X	X	X	X	X
Support Of Carrier CC&T Interfaces	X	X	X	X	X
Scripted Control Of Process Steps	X		X	X	X
Automated Health And Safety	X	X	X	X	X
Non-Volatile Storage Of In-Flight Mission Changes	X	X	X	X	X
Ground Station					
Archiving/Playback Of Telemetry	X	X	X	X	X
Command Generation	X	X	X	X	X
Display And Analysis Of Science/Engineering Data	X	X	X	X	X
Support NASA/Commercial Ground Station Interfaces	X	X	X	X	X
Configuration Control	X	X	X	X	X
Distribution Of Telemetry Via Internet			X	X	X

ECS/ECS-II DISTRIBUTED SYSTEM ARCHITECTURE

The decision to use a distributed system architecture constructed of COTS components was driven by factors including:

- low cost
- use of commercial software packages
- 100% compatibility of software between ground development and flight systems
- parallel development capability on non-flight ground system
- established set of development tools

Both the ECS and ECS-II are designed using the same overall system architecture. The major difference is the use of COTS hardware to implement the servo subsystem in the ECS-II. Figure 4 shows the migration from the terrestrial architecture to the ECS/ROMPS architecture, then to the ECS-II/ AWCS architecture.

USE OF COTS SINGLE-BOARD COMPUTERS AND PERIPHERALS

First and foremost to meet our commercial customer objectives, the use of COTS components reduces the cost of experimental systems. Second, COTS components accelerate the space investigator's access to familiar or state-of-the-art technology.

Reduced Cost

While it is difficult to compare the cost of conventional space "qualified" systems with space "ruggedized" systems, the following comparisons are of interest:

- An accepted estimate of developing full space qualified avionics systems (with the same mass as the ECS) ranges from $1.1M to 7.6M.[3]

- Our approach, maximizing COTS content and accepting system reliability estimates of 97 percent versus 99.99 percent, reduced the actual cost (including mission support) to $750K for ROMPS.

Acceleration of Technology Introduction

As shown in Table 2, the introduction of computers to space missions has significantly lagged behind the same technology's commercial introduction. While a significant element of the lag is the lengthy and costly delay associated with radiation hardening, there are many missions that do not require this characteristic. One of our goals is to accelerate the introduction of a new computing capability where the need for high performance at low cost outweighs susceptibility to radiation.

In the upgrade of the ECS to the ECS-II one COTS module, a DSP based servo controller, allowed the replacement of three custom modules. This change increased the servo loop rate by a factor of 80, and also allows the use of both stepper and servo motors.

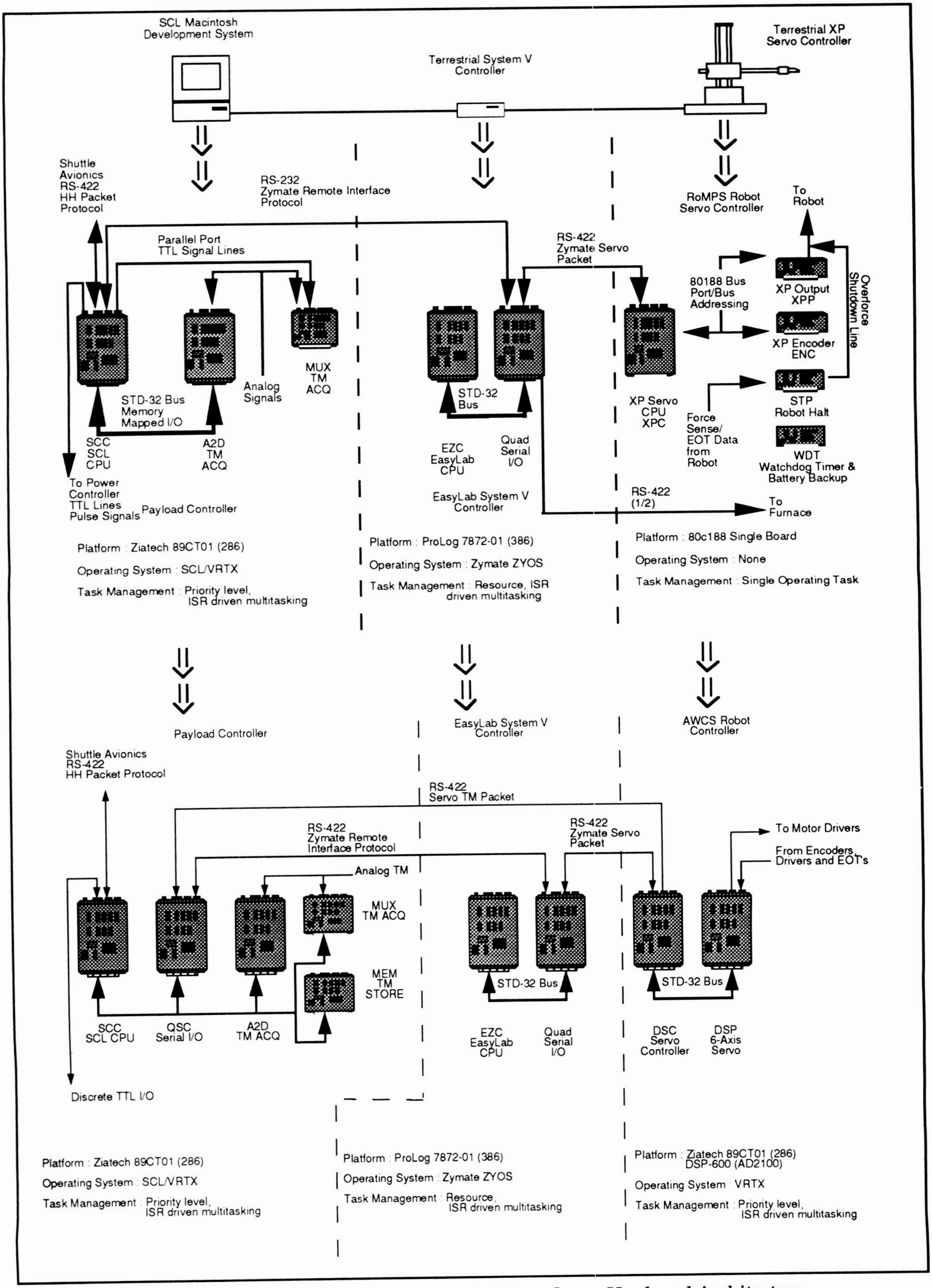


Figure 4. Migration of Terrestrial Architecture to a Space-Hardened Architecture

Table 2. Technology Introduction Acceleration

Computer Technology	Commercial Introduction	Space Mission Launch	Delay in Years
x186/188 also PC-XT	1983	1989	6
x286 also PC-AT	1984	1989 est	5
x386	1988	1993 est	5
x486	1989	1995 est	6
Pentium	1993	1996 est	3
PowerPC	1994	1996 est	2
R6000	1995	1996 est	1

Rapidly Increasing COTS Content

In less than three years, we have gone from systems with no COTS content to systems with better than 60 percent COTS content (see Table 3). In 1992 we achieved 50 percent COTS contents; by 1996 we are planning systems with 80 percent COTS content. With each new customer and program, we continue to reduce the custom content of our systems while we improve performance.

Table 3. COTS Content Increase

	ARD 1992	ROMPS 1994	AWCS 1996	ROMPS-2 1997
Custom modules	4	4	2	2*
COTS modules	4	6	9	7
% COTS content	50 %	60 %	81%	78%

*Both custom modules are reused designs.

THE FLIGHT SEGMENT ARCHITECTURE

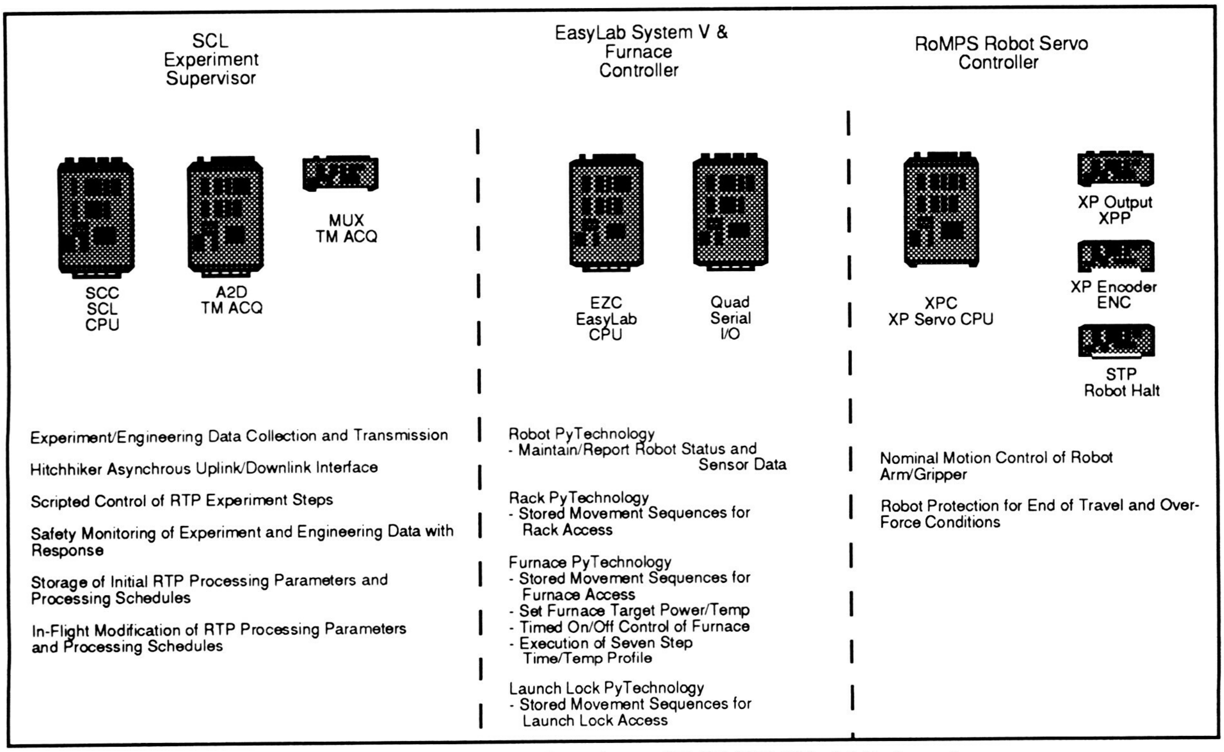
Figures 5 and 6 summarize the mapping of functional requirements onto the flight subsystems of the ECS and ECS-II systems. These figures also reveal the hierarchical levels of experiment control performed by the different subsystems. Moving from the SCL Experiment Supervisor on the far left to the Robot Servo Controller on the far right, the command interfaces become less abstract and more device-specific.

At the SCL Experiment Supervisor, the control of the experiment is at a very high abstraction level. This subsystem monitors the health and safety of the payload and halts the automation scripts if it detects an anomalous condition, such as temperature, of the motor drivers exceeding the safe operating limit.

During the ROMPS mission this subsystem executed the RTP processing scripts, which set sample processing parameters and initiated laboratory unit operations by sending commands to the Zymate System V Controller.

During the WSF-3/AWCS mission this subsystem will execute the Substrate Transfer scripts, which moves a specific wafer between its storage station, the rotator, a cooling station, and finally back to its storage station.

In both cases, the Zymate System V Controller executes the steps of the laboratory unit operations initiated by the SCL Experiment Supervisor. Device-specific commands are sent to the Robot Servo Controller to complete these laboratory unit operations.



Experiment/Engineering Data Collection and Transmission

Hitchhiker Asynchrous Uplink/Downlink Interface

Scripted Control of RTP Experiment Steps

Safety Monitoring of Experiment and Engineering Data with Response

Storage of Initial RTP Processing Parameters and Processing Schedules

In-Flight Modification of RTP Processing Parameters and Processing Schedules

Robot PyTechnology
- Maintain/Report Robot Status and Sensor Data

Rack PyTechnology
- Stored Movement Sequences for Rack Access

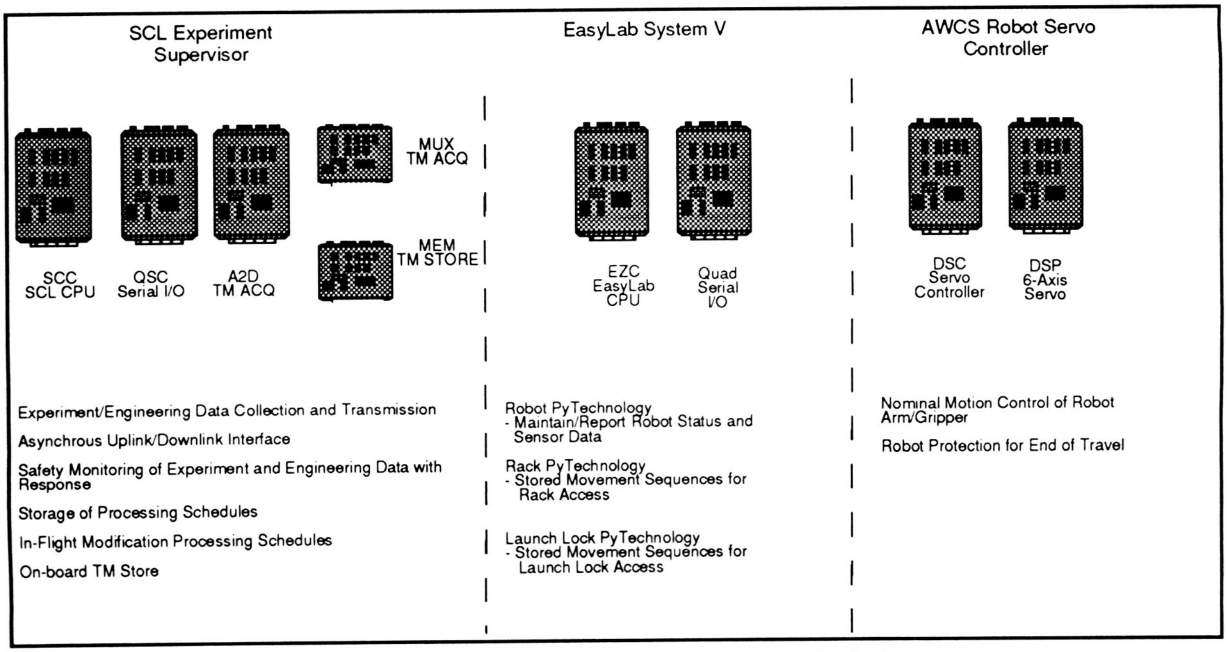
Furnace PyTechnology
- Stored Movement Sequences for Furnace Access
- Set Furnace Target Power/Temp
- Timed On/Off Control of Furnace
- Execution of Seven Step Time/Temp Profile

Launch Lock PyTechnology
- Stored Movement Sequences for Launch Lock Access

Nominal Motion Control of Robot Arm/Gripper

Robot Protection for End of Travel and Over-Force Conditions

Figure 5 - Requirements Mapping of ROMPS Flight Subsystems



Experiment/Engineering Data Collection and Transmission

Asynchrous Uplink/Downlink Interface

Safety Monitoring of Experiment and Engineering Data with Response

Storage of Processing Schedules

In-Flight Modification Processing Schedules

On-board TM Store

Robot PyTechnology
- Maintain/Report Robot Status and Sensor Data

Rack PyTechnology
- Stored Movement Sequences for Rack Access

Launch Lock PyTechnology
- Stored Movement Sequences for Launch Lock Access

Nominal Motion Control of Robot Arm/Gripper

Robot Protection for End of Travel

Figure 6 - Requirements Mapping of AWCS Flight Subsystems

Many of the disadvantages of a distributed architecture are eliminated in this system by the use of simple, robust, and well-tested communication protocols.

THE GROUND SEGMENT ARCHITECTURE

The ground station architecture also makes use of a distributed architecture. Figure 7 summarizes the mapping of functional requirements onto the ground station subsystems of the Experiment Control System. Again, the hierarchical levels of command and control are shown. Decreasing levels of experiment control abstraction are shown as one proceeds from left to right across this figure.

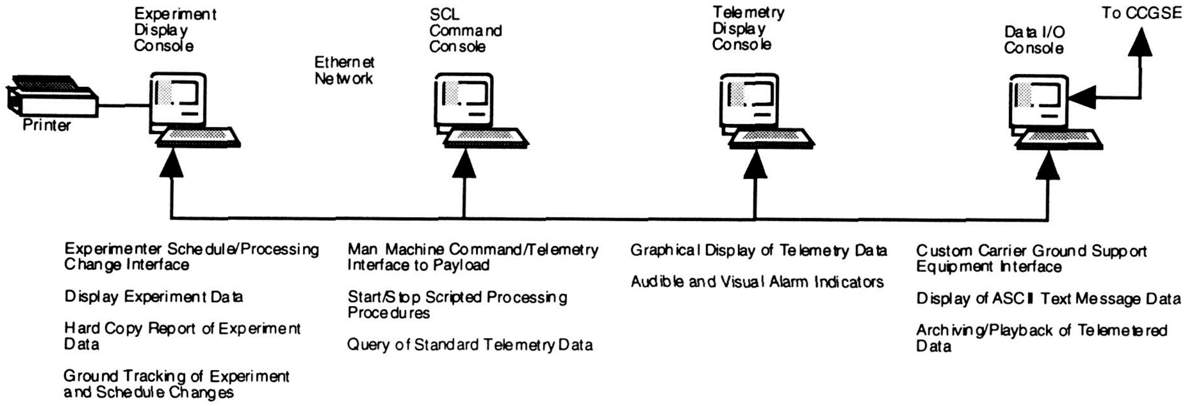


Figure 7. Requirement Mapping of Ground Station Subsystems

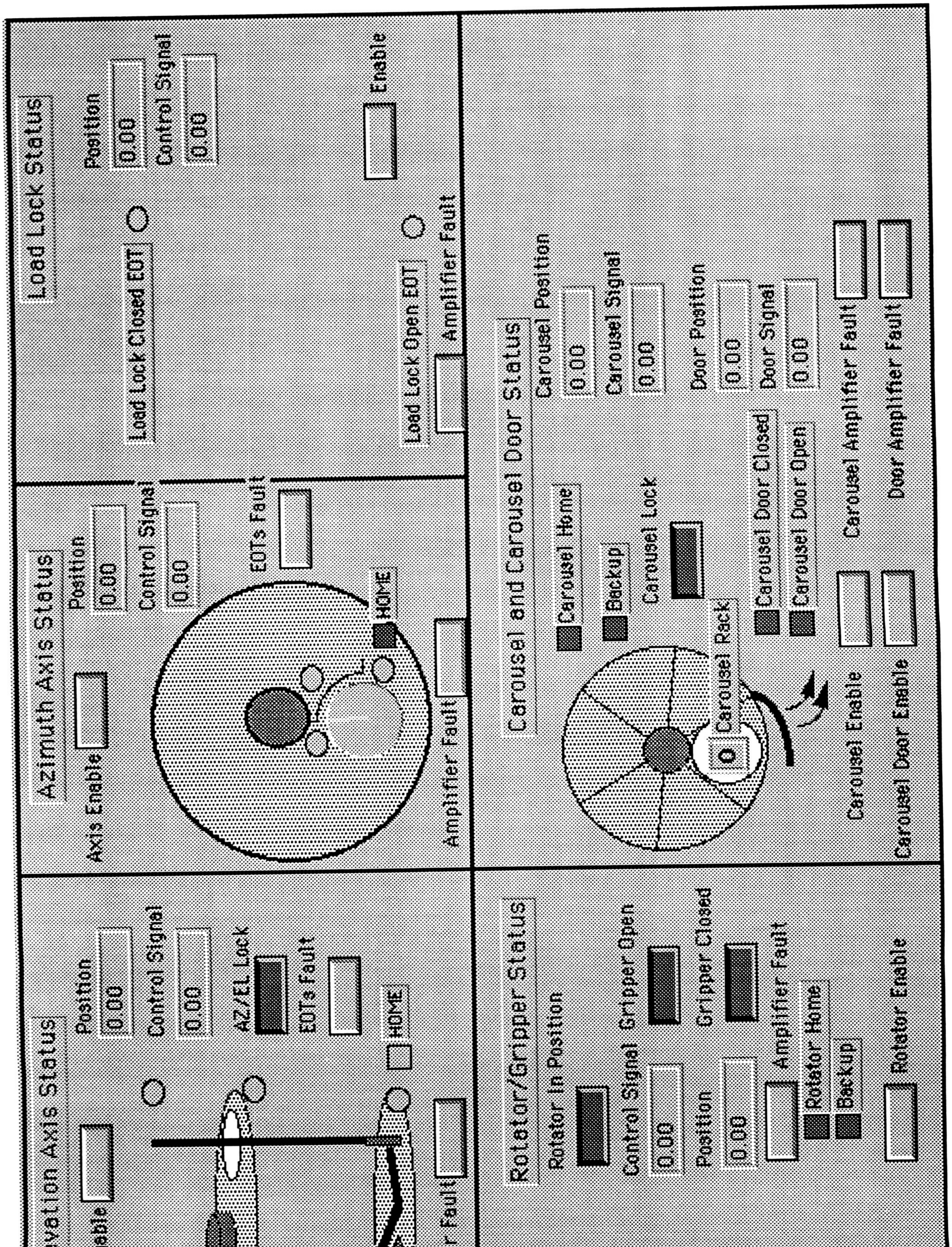
At the far left, the Experiment Display Console allows the primary investigators to extract specific data from archived telemetry, allowing creation of reports. Additionally, the primary investigators use a set of spreadsheets to generate updated scripts to be executed against the on-board sample processing and schedule parameters. These updated scripts are then sent to the payload operator for preparation for upload to the payload.

The SCL Command Console is used by the payload operator to command the payload. Commands are processed by the SCL Command Console's compiler and transmitted to the Data I/O Console for upload to the payload. The SCL Command Console is also responsible for running ground side rules and scripts.

The Telemetry Display Console is a graphical display of the incoming telemetry. This graphical display is done using LabView®, see Figure 8 & Figure 9. The items being displayed are easily changed by opening another LabView Virtual Instrument® (VI). This allows an easy method to switch between engineering and science data displays. It is also possible to have more than one Telemetry Display Console.

At the Data Input/Output (I/O) Console, incoming telemetry from the payload is archived, and changed telemetry items are broadcast on the network for the other consoles. The Data I/O Console is also responsible for archiving incoming telemetry data, displaying text messages from the payload, and uploading the compiled command data sent from the attached SCL Command Console.

The Telemetry Display Console and the SCL Command Consoles receive updates for their local telemetry databases across the Ethernet network. These data are placed on the Ethernet network by the Data I/O Console.



Elevation Axis Status: Position 0.00; Control Signal 0.00

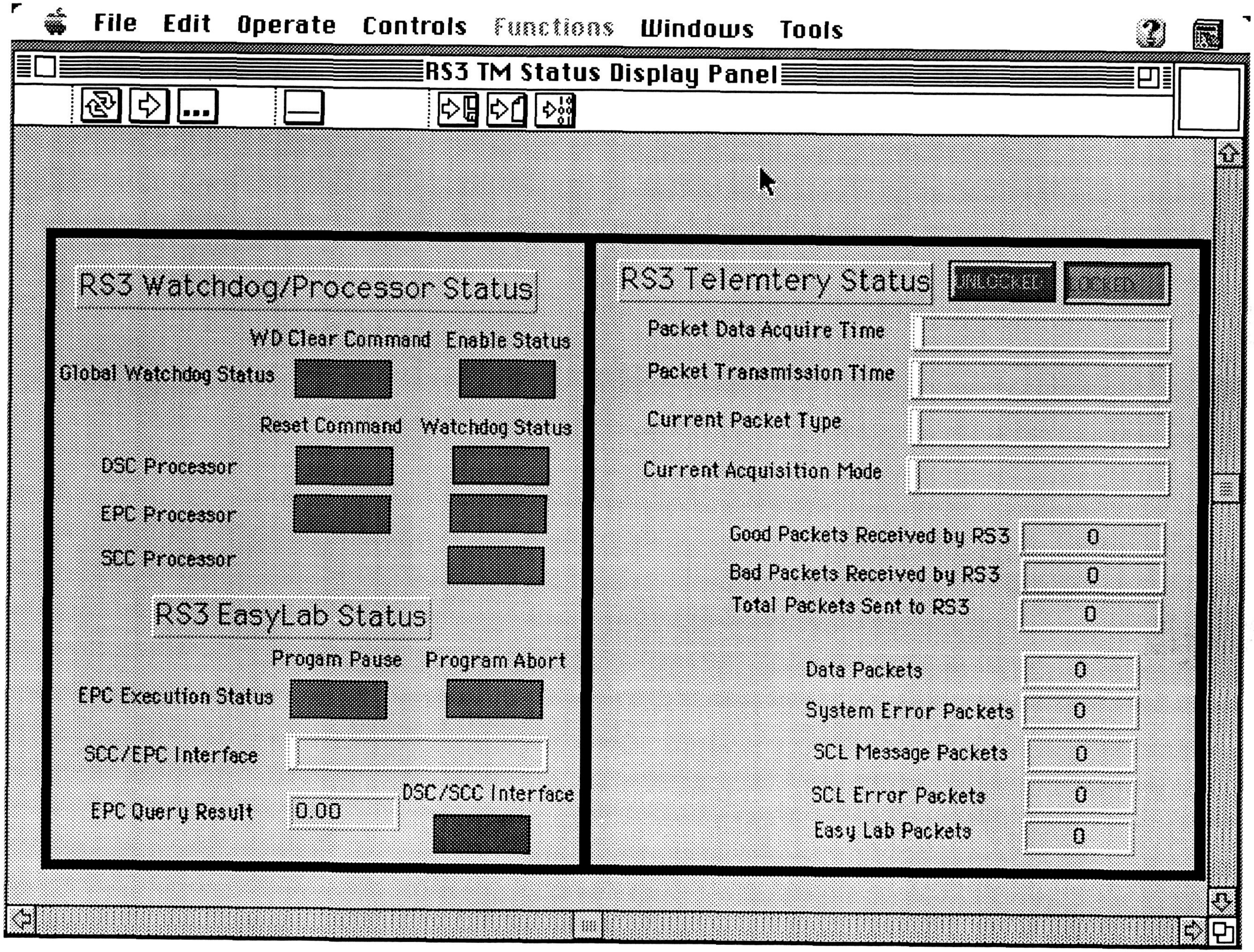
Azimuth Axis Status: Position 0.00; Control Signal 0.00

Load Lock Status: Position 0.00; Control Signal 0.00

Rotator/Gripper Status: Control Signal 0.00; Position 0.00

Carousel and Carousel Door Status: Carousel Position 0.00; Carousel Signal 0.00; Door Position 0.00; Door Signal 0.00

Figure 8 - Robot Telemetry LabView® Display



EPC Query Result 0.00

Good Packets Received by RS3 0
Bad Packets Received by RS3 0
Total Packets Sent to RS3 0

Data Packets 0
System Error Packets 0
SCL Message Packets 0
SCL Error Packets 0
Easy Lab Packets 0

Figure 9 - Payload Processor Health LabView® Display

All of the application programs that make up the ground station use the standard Macintosh window/icon/pointer/mouse user interface paradigm. This allows users to concentrate on learning the functionality of the applications without worrying about the details of the human-machine interface.

MISSION OPERATIONS FOR MATERIAL PROCESSING PROCEDURES

One of the driving philosophies of the ECS/ECS-II system architecture is to enable the PIs to interact with the payload in a meaningful way without the need of a payload operator to translate every command request into a set of payload directives. To meet this requirement, it was necessary to identify the operations the PIs would be interested in initiating and the telemetry data that would be of immediate value to them during mission operations. To accommodate this method of command and control, a set of on-board SCL mission scripts was implemented that would take as an input a list of samples to be processed. These scripts would then access a global table containing the processing parameters for all the samples aboard the payload.

To enable the PIs to interact with the payload, it was necessary to provide them with a data-entry mechanism for specifying a list of samples to be processed, and the processing parameters for these samples. It was decided that because this data was essentially tabular in nature, a spreadsheet could be used as the data input mechanism. Custom spreadsheet macros allow the user to generate lists of samples to be processed and to specify processing parameters. These macros create ASCII files to be compiled by SCL into scripts, which are uploaded and executed by the payload operator.

The ROMPS mission required that the PI's be able to specify up to seven time/temperature profiles for each sample. Additional, the PI's were able to specify which samples were to be processed during an operational period.

The upcoming WSF/AWCS missions contain very different requirements. The WSF3/AWCS mission is simpler than that of the ROMPS mission. During this mission SCL controls only the transfer of single substrates since all processing is controlled by the PI's on the ground. The PI's will indicate which substrate they want and the operator will execute the Substrate Transfer script using the substrate number as an argument.

It is expected that the WSF-4/AWCS mission requirements will be much more demanding. All factors of the MBE processing cycle will be controlled by the ECS-2. This includes substrate transfer, substrate heating, source cell heating, source cell shutter control and RHEED processing. SCL will be used for overall process control through the use of its script and rules. The RHEED processing will be done by a dedicated vision processing engine, which along with other sensors will provide SCL with the information needed to process the substrate. The PI's will again use a spreadsheet to enter the information regarding the process parameters.

POST-MISSION DATA ANALYSIS

During the mission, data are archived by the DataIO application running on the data I/O console into playback files. These playback files archive the incoming telemetry packets and the outgoing command packets. The DataIO application can replay these play-back files and will drive all the attached processes as if the data were coming in real time. This allows the LabView application running on the Experiment Display Console to display archived data in order to review mission events. When playing back archive file, DataIO can preserve the relative time domain in which the telemetry occurred or at the maximum speed that the system is capable of performing.

In addition to the ability to drive attached telemetry display applications, the DataIO application can produce spreadsheet importable text files containing selected telemetry items. DataIO performs the necessary data translations so the telemetry items are presented in user units.

CONCLUSION

The ECS for the ROMPS payload was completed in just 13 months with delivery of over 30,000 lines of source code, three space-hardened computer systems, and the electrical harnessing to connect them. The staffing of this project included two full-time software engineers, two software contractors, one full-time electrical engineer, one part-time mechanical engineer, one part-time assembly technician, and three co-op students. ROMPS flew on STS-64 where it successfully accomplished all of the primary and secondary objectives, well ahead of the mission schedule. The high level scripting and expert rule evaluation capability of the ECS was the key to achieving the early completion of all mission objectives.

AMPS has invested in the productization of the ECS and is offering the ECS-II system for sale as the first affordable off-the-shelf option for low cost missions. Ideal applications include the Hitchhiker and INSTEP programs.

AMPS-SR's ongoing challenge is to adapt the ECS-II to automate the MBE processing methods that will be performed by ground operators on WSF-3. This mission will extend the capabilities of the ECS with the addition of process control and process sensors. Keeping with the COTS philosophy, and modular architecture, this set of new capabilities will include pre-integrated add-on modules that perform real-time machine vision and indirect temperature sensing for the purpose of in-line process control.

All low earth orbit researchers can benefit from simple control of their experiments and faster turn-around of mission data.

REFERENCES

1. L.J. Hansen and C.H. Pollock, *Space Mission Analysis and Design,* 2nd edition, Kluwer Academic Publishers, Boston, Chapter 16, p. 609, 1992.

2. L.J. Hansen and C.H. Pollock, *Space Mission Analysis and Design,* 2nd edition, Kluwer Academic Publishers, Boston, Chapter 16, p. 616, 1992.

3. R. Wong, *Space Mission Analysis and Design,* 2nd edition, Kluwer Academic Publishers, Boston, Chapter 20, p. 666, 1992.

4. L.D. Negron, Jr. and A. Chomas, *Space Mission Analysis and Design,* 2nd edition, Kluwer Academic Publishers, Boston, Chapter 14, p. 556, 1992.

ACKNOWLEDGMENTS

AMPS would like to acknowledge the NASA Goddard Space Flight Center personnel who funded the ECS effort under NAGW-1198, NAG5-1517, and NAS5-32471. We deeply appreciated this research and development opportunity, and their willingness and support throughout this unorthodox and challenging effort. Similarly, this program could not have been accomplished without the tireless technical and financial support of the two commercial product vendors—the team at Interface and Control Systems for accomplishing many modifications and improvements to SCL, and the Zymark Corporation for their support in modifying the Easylab and the XP servo software. Our thanks to the many unnamed individuals who contributed invaluable effort and advice when it was most needed.

TRADEMARK NOTICES

Spacecraft Command Language is a registered trademark of Interface and Control Systems Inc.
Zymate, Zymark, EasyLab, PyTechnology, and System V are registered trademarks of Zymark Corporation.
Apple, AppleTalk, and Macintosh are registered trademarks of Apple Corporation.
STD 32 is a registered trademark of Ziatech Corporation.
All other products mentioned are trademarks of their respective companies.