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# KNOWLEDGE BASED AND INTERACTIVE CONTROL FOR THE SUPERFLUID HELIUM ON-ORBIT TRANSFER PROJECT

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## Abstract

NASA's Superfluid Helium On-Orbit Transfer (SHOOT) project is a Shuttle-based experiment designed to acquire data on the properties of superfluid helium in micro-gravity. Aft Flight Deck Computer Software for the SHOOT experiment is comprised of several monitoring programs which give the astronaut crew visibility into SHOOT systems and a rule based system which will provide process control, diagnosis and error recovery for a helium transfer without ground intervention. Given present Shuttle manifests, this software will become the first expert system to be used in space. The SHOOT Command and Monitoring System (CMS) software will provide a near real time highly interactive interface for the SHOOT principal investigator to control the experiment and to analyze and display its telemetry. The CMS software is targeted for all phases of the SHOOT project: hardware development, pre-flight pad servicing, in-flight operations, and post-flight data analysis.

## Introduction

The SHOOT experiment is a demonstration of the critical technology required to service cryogenically cooled satellites in a micro-gravity environment. Superfluid helium has a number of unusual properties including zero viscosity, very high thermal conductivity, and a thermo-mechanical effect in which the helium is "attracted" to heat. The experiment will be controlled continuously during a four to seven day mission by a scientist at a Payload Operations and Control Center (POCC) or by an astronaut on the Aft Flight Deck (AFD) of the shuttle orbiter. Mission objectives for SHOOT include demonstrating the transfer of superfluid helium between two dewars, verifying the design of a superfluid helium transfer line and man rated fluid coupler, demonstrating a technique called heat pulse mass gauging to very accurately determine the amount of helium present and the

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§ Sterling Software, Palo Alto, California onboard control of a helium transfer without ground intervention. All of these are necessary for the future development of NASA's Superfluid Helium Tanker (SFHT) which will NASA's next generation of astrophysical observatories in low earth orbit (i.e., SIRTF, AXAF, ASTROMAG).

Some of these objectives are best accomplished by an expert operator from the POCC, others must be accomplished by a shuttle crewman having real time visibility and control of SHOOT systems. As a result, the operations and control software has been divided into two separate and distinct parts. Each has its own capabilities tailored for the environment, specific operations, and level of expertise of the operator. POCC software is designed to preserve the maximum operational flexibility for an expert operator during all phases of SHOOT hardware use including pre, post and in-flight experiments. AFD software is designed to provide a non-expert shuttle crewmember with the specific information and control functions for a given experiment phase. Diagnostics and error handling are provided for off nominal conditions.

## Experiment Overview

The SHOOT experiment consists of a series of transfers between two dewars in the shuttle cargo-bay. Each dewar (Figure 1.) is heavily instrumented with temperature, pressure and fluid level sensing devices. Operators at the POCC can select individual devices to read and display through commands sent to the SHOOT electronics on the shuttle (Figure 2.). Data that is received at the POCC is converted to meaningful units, limit checked and archived in real time. In this way the experiment control computer at the POCC is the experiment PI's interface to the flight hardware. Most operations are performed under POCC control.

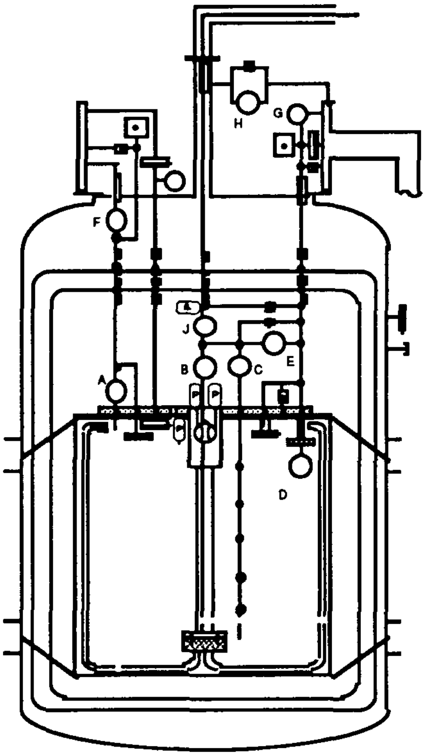


**Figure 1. The SHOOT dewar and cryostat**

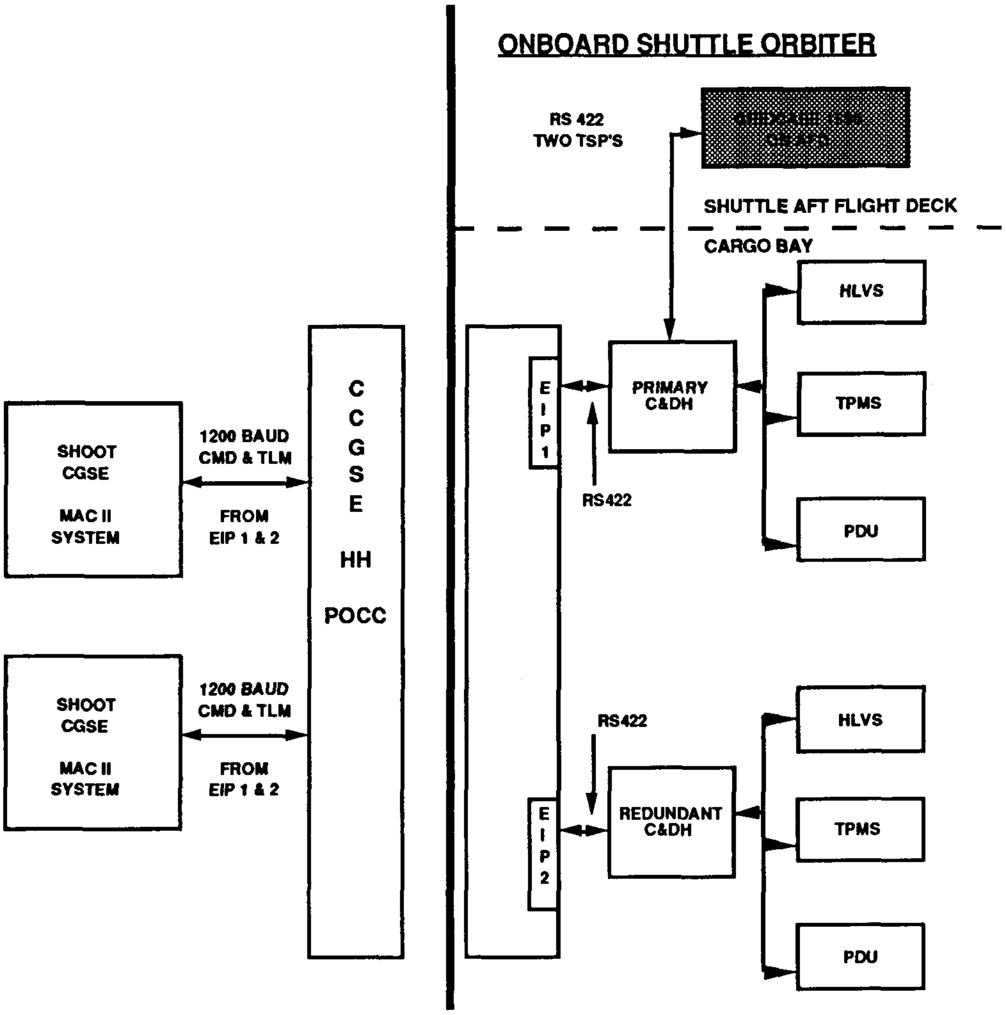
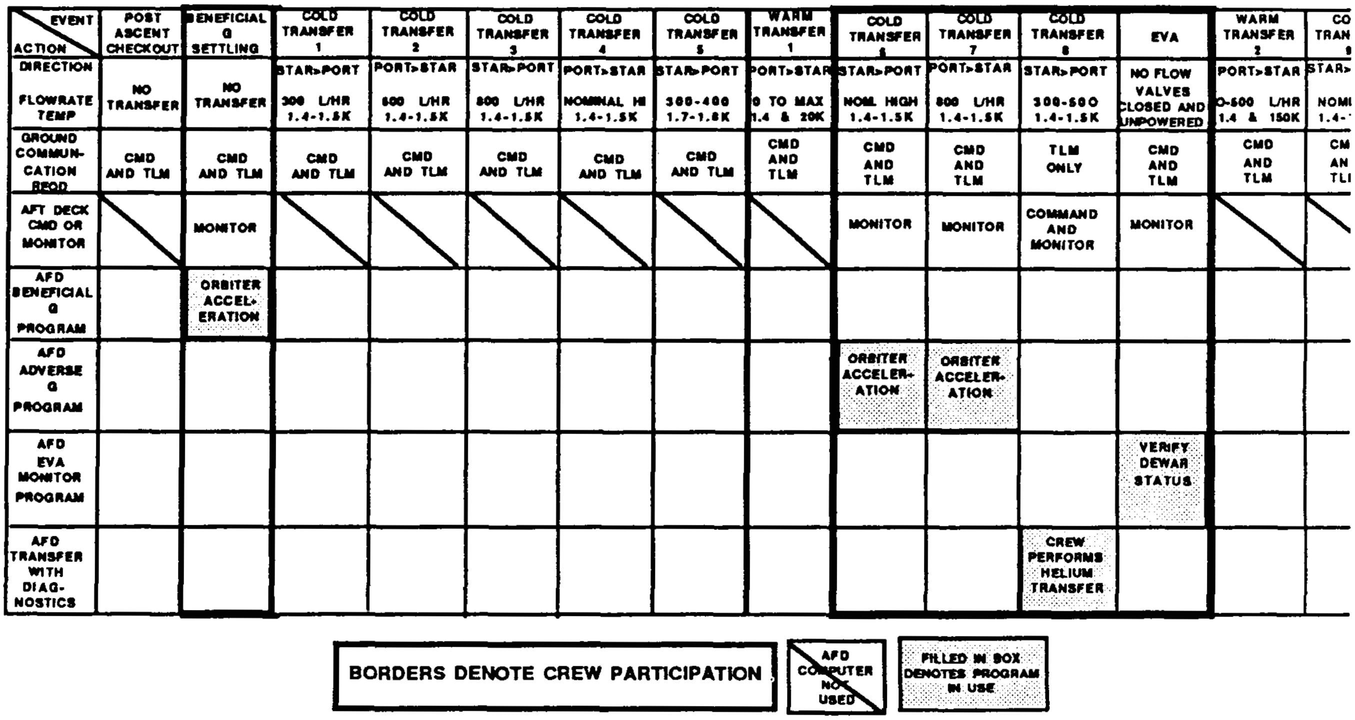


Figure 2. Block Diagram of the SHOOT Electronics

Legend: C&DH-Command and Data Handling Unit, HLVS-Heater, Level Detector Valve Driver System, TPMS-Temperature and Pressure Measurement System, CCGSE-Customer Carrier Ground Support Equipment, EIP-Experiment Interface Panel

Certain operations require testing the ability of the SHOOT Fluid Acquisition apparatus to pump helium during normal orbiter attitude maintenance maneuvers. Since the SFHT will be shuttle based verifying this capability is of prime importance to achieving the SHOOT science objectives. This involves real-time, graphical feedback to the crew during Reaction Control System jet firings. The crew will initiate the firing during a helium transfer and observe the system performance in real time. Upon observation of a loss of flow condition the acceleration is to be terminated and the ability of the flow to restart observed. Other operations such as the Beneficial Acceleration Settling and the Extra-Vehicular Activity (EVA) Monitoring function are also best performed onboard. Monitoring programs specific to these functions will be provided for the crew's use.



| EVENT / ACTION | POST ASCENT CHECKOUT | BENEFICIAL G SETTLING | COLD TRANSFER 1 | COLD TRANSFER 2 | COLD TRANSFER 3 | COLD TRANSFER 4 | COLD TRANSFER 5 | WARM TRANSFER 1 | COLD TRANSFER 6 | COLD TRANSFER 7 | COLD TRANSFER 8 | EVA | WARM TRANSFER 2 | CO TRAN 9 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| DIRECTION<br>FLOWRATE TEMP | NO TRANSFER | NO TRANSFER | STAR>PORT<br>300 L/HR<br>1.4-1.5K | PORT>STAR<br>600 L/HR<br>1.4-1.5K | STAR>PORT<br>800 L/HR<br>1.4-1.5K | PORT>STAR<br>NOMINAL HI<br>1.4-1.5K | STAR>PORT<br>300-400<br>1.7-1.8K | PORT>STAR<br>0 TO MAX<br>1.4 & 20K | STAR>PORT<br>NOM. HIGH<br>1.4-1.5K | PORT>STAR<br>800 L/HR<br>1.4-1.5K | STAR>PORT<br>300-500<br>1.4-1.5K | NO FLOW<br>VALVES CLOSED AND UNPOWERED | PORT>STAR<br>0-600 L/HR<br>1.4 & 150K | STAR><br>NOMI<br>1.4- |
| GROUND COMMUNCATION REQD | CMD AND TLM | CMD AND TLM | CMD AND TLM | CMD AND TLM | CMD AND TLM | CMD AND TLM | CMD AND TLM | CMD AND TLM | CMD AND TLM | CMD AND TLM | TLM ONLY | CMD AND TLM | CMD AND TLM | CM AN TLI |
| AFT DECK CMD OR MONITOR | ╲ | MONITOR | ╲ | ╲ | ╲ | ╲ | ╲ | ╲ | MONITOR | MONITOR | COMMAND AND MONITOR | MONITOR | ╲ | ╲ |
| AFD BENEFICIAL G PROGRAM | | ORBITER ACCEL-ERATION | | | | | | | | | | | | |
| AFD ADVERSE G PROGRAM | | | | | | | | | ORBITER ACCELER-ATION | ORBITER ACCELER-ATION | | | | |
| AFD EVA MONITOR PROGRAM | | | | | | | | | | | | VERIFY DEWAR STATUS | | |
| AFD TRANSFER WITH DIAG-NOSTICS | | | | | | | | | | | CREW PERFORMS HELIUM TRANSFER | | | |

BORDERS DENOTE CREW PARTICIPATION

╲ AFD COMPUTER NOT USED

▨ FILLED IN BOX DENOTES PROGRAM IN USE

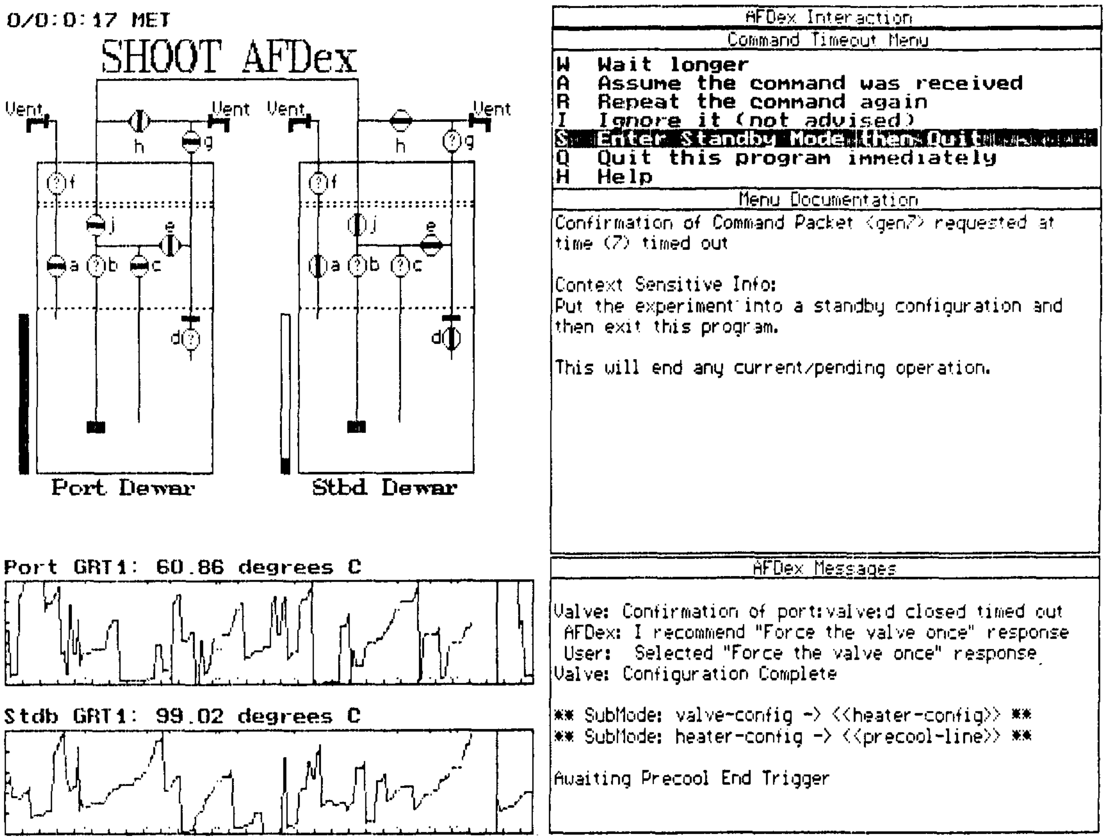
Figure 3. Matrix showing the division of control between the ground and crew

The SFHT will contain many thousands of liters of helium if it is to meet the requirements of large space based observatories. Fluid transfer rates up to 1000 liters per hour are conceivable. Even at this flow rate a satellite resupply is a multi-hour process. The objective of the AFD expert system is to demonstrate the ability to control a helium transfer operation autonomously from orbit without crew or ground intervention.

## Aft Flight Deck Software

Four programs are being developed to support SHOOT science objectives from the Aft Flight Deck. Three of these are for monitoring only, while the fourth will demonstrate the autonomous control of cryogen transfer in space without ground intervention.

AFDex (\'af-dek\) is a rule-based system under development at the NASA Ames Research Center for the SHOOT experiment, which will operate on the Space Shuttle's Aft Flight Deck (AFD) computer. The primary goal of AFDex is to provide intelligent process control, diagnosis, and error recovery capabilities for the transfer of superfluid helium between two dewars in the orbiter's cargo bay. During a nominal transfer, AFDex is responsible for sending commands which control the payload, monitoring telemetry from the payload, and providing a graphical display which reflects the current state of the dewars and the transfer. In the event of an abnormal condition, AFDex must diagnose the condition and formulate plans for error recovery. Diagnosis is associative (based upon relationships between symptoms and causes) as opposed to a model-based approach which would be too inefficient for this application.



```
Confirmation of Command Packet <gen7> requested at
time (7) timed out

Context Sensitive Info:
Put the experiment into a standby configuration and
then exit this program.

This will end any current/pending operation.
```

```
Valve: Confirmation of port:valve:d closed timed out
 AFDex: I recommend "Force the valve once" response
 User:  Selected "Force the valve once" response
Valve: Configuration Complete

** SubMode: valve-config -> <<heater-config>> **
** SubMode: heater-config -> <<precool-line>> **

Awaiting Precool End Trigger
```

**Figure 4. Display of AFDex during Precool Phase**

Although the system is designed to automate the transfer operation, AFDex has facilities to interact with the astronauts. Data which is relevant to a current operation is displayed graphically. An astronaut may guide the system's behavior (i.e. select an error recovery strategy) via menus and input fields. Input is asynchronous and preemptable. Asynchrony allows the system to continue reasoning about events while interacting with the user. Preemptability allows the system to interrupt a current interaction in response to some event.

AFDex receives data via a serial connection through the Hitchhiker carrier's avionics. Since the system must respond in real-time to to events represented in this data stream, a number of mechanisms have been developed to reduce the effort of processing payload data. The system may be viewed as consisting of three components: the payload avionics, a telemetry preprocessor, and the rule-based system. At the lowest level, AFDex may command the avionics hardware to control what data it receives from the payload and at what rate. This provides a coarse-grained, low overhead filter suitable for specific operations although it has limited flexibility and nontrivial operational complexity.

Once telemetry is received by the Aft Flight Deck computer from the payload avionics, a preprocessor is used to focus attention on certain classes of data (to the exclusion of others) from which it will create facts to assert into the expert system knowledge base. The behavior of this preprocessor is dynamically controlled by the expert system. In an effort to reduce the overhead of processing large amounts of invariant data, the preprocessor may be commanded to report only relevant changes in data values. Additional preprocessing may include qualitative analysis (i.e. from 23 degrees to warm), constraint demons (alert if GRT-12 and GRT-35 are the same temperature), and deviation from anticipated (simulated) values. Data from the preprocessor is asserted into a Rete network [Forgy] which efficiently handles pattern matching and rule invocation. Within the expert system a number of strategies (modalities, prioritized agenda, rule partitioning, etc.) are used to focus attention and respond efficiently to events.

AFDex is being developed in CLIPS (a derivative of OPS-5 and ART developed by NASA) and C for delivery on a 386-based GRiD 1530 laptop computer. The current system has knowledge concerning command generation and receipt, valve devices, germanium resistance thermometers, all operations required for nominal transfer, and simulation of certain error modes for each device. This is captured in a knowledge-base currently consisting of 84 rules and 114 initial facts. The capabilities and size of the system will increase significantly as development continues.

SHOOT utilizes three additional programs on the Aft Flight Deck computer. These programs provide real-time monitoring capabilities during specific SHOOT operations. Currently these programs have no commanding capability and thus are dependent upon ground control. We are currently evaluating the option of embedding these programs within rule-based systems similar to AFDex. This would allow certain mission objectives to be achieved in the event of an extended loss of ground communication.

Knowledge-based process control and diagnosis has proved effective in the development of AFDex. A rule-based approach provides a natural framework to develop a system in which multiple threads of execution are inherent. There are potentially many actions possible at any time, and each action may be only slightly related to any other action. Diagnosis is unobtrusively interleaved with control. Rules provide an excellent mechanism for applying large amounts of very specific knowledge in response to changes in the environment. CLIPS has proved to be a fast, compact, and portable system which is able to represent this knowledge and apply it in real-time. This is complemented by the availability of all source code which allows CLIPS to be customized and embedded in an arbitrary application. More significantly, AFDex demonstrates that expert systems have become a mature technology which is being integrated into aerospace operations.

## Shoot Ground Based Command and Monitoring System

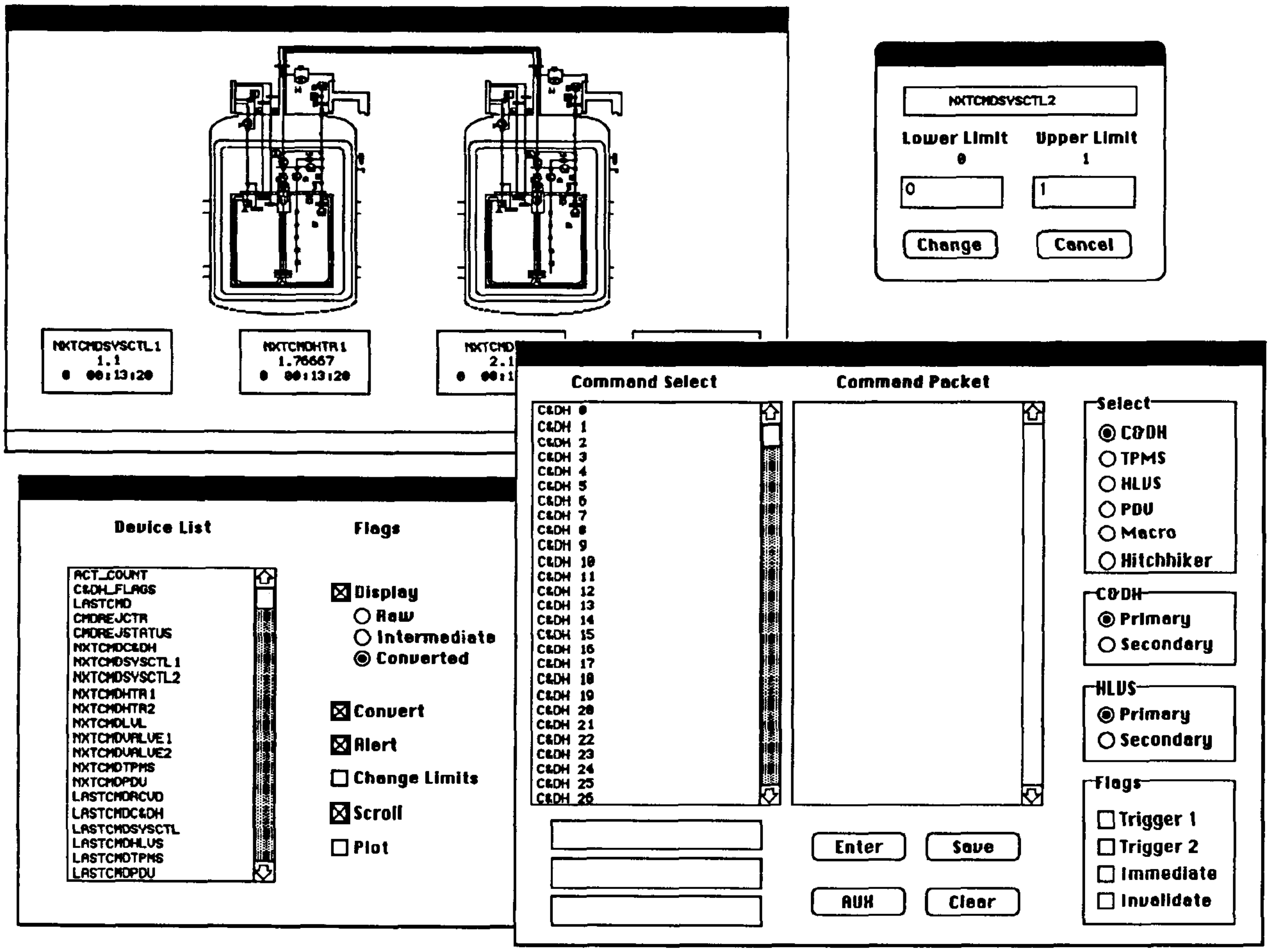
### Design

The goal in designing the SHOOT Command and Monitoring System (CMS) software was to create a system that is easy to use as possible while retaining full control of the experiment at a low level for maximum flexibility. Because the SHOOT experiment is highly interactive and will be controlled for extended periods of time, a good user interface is very important. The Macintosh's icon based point-and-click environment provides quick and easy methods for performing complicated tasks.

The user interface of the CMS was fully prototyped before any coding was done and drove the design of the software using a top down approach. Windows were designed from the user's perspective (a specialist in cryogenics) to perform each function required.

Flexibility will allow the software to be reusable for all aspects of the experiment including early tests with the hardware, system level integration, servicing the experiment while in the payload bay of the shuttle on the launch pad, and operations during and after flight.

Should the CMS become overloaded it is designed to degrade gracefully. Every function in the system has a certain priority; lower priority operations will be gradually phased out until higher priority operations have time to catch up. (Figure 5.)



NXTCMDSYSCTL1
1.1
0 00:13:20

NXTCMDHTR1
1.76667
0 00:13:20

NXTCMD
2.1
0 00:1

NXTCMDSYSCTL2

Lower Limit 0 — Upper Limit 1

Lower Limit: 0

Upper Limit: 1

Device List

ACT_COUNT
C&DH_FLAGS
LASTCMD
CMDREJCTR
CMDREJSTATUS
NXTCMDC&DH
NXTCMDSYSCTL1
NXTCMDSYSCTL2
NXTCMDHTR1
NXTCMDHTR2
NXTCMDLVL
NXTCMDVALVE1
NXTCMDVALVE2
NXTCMDTPMS
NXTCMDPDU
LASTCMDACVD
LASTCMDC&DH
LASTCMDSYSCTL
LASTCMDHLVS
LASTCMDTPMS
LASTCMDPDU

Flags

☒ Display
○ Raw
○ Intermediate
● Converted

☒ Convert
☒ Alert
☐ Change Limits
☒ Scroll
☐ Plot

Command Select

C&DH 0
C&DH 1
C&DH 2
C&DH 3
C&DH 4
C&DH 5
C&DH 6
C&DH 7
C&DH 8
C&DH 9
C&DH 10
C&DH 11
C&DH 12
C&DH 13
C&DH 14
C&DH 15
C&DH 16
C&DH 17
C&DH 18
C&DH 19
C&DH 20
C&DH 21
C&DH 22
C&DH 23
C&DH 24
C&DH 25
C&DH 26

Select
● C&DH
○ TPMS
○ HLVS
○ PDU
○ Macro
○ Hitchhiker

C&DH
● Primary
○ Secondary

HLVS
● Primary
○ Secondary

Flags
☐ Trigger 1
☐ Trigger 2
☐ Immediate
☐ Invalidate

**Figure 5. Prototype CMS display showing telemetry, command and status windows**

## Implementation

The SHOOT Command and Monitoring System is being developed on a Macintosh II using the Macintosh Programmers Workshop (MPW) Toolset and is being written in C. The event oriented operating system on the Macintosh enables simultaneous user interaction and internal processing to occur without having multiple processes.

Priority is highest for archiving and calibrating telemetry, followed by commanding operations and updating the display. Two identical systems will be used during flight at the POCC for redundancy, each capable of performing everything required to conduct the experiment. Only one system will be allowed to up-link commands at a time. The other system may be used for more time consuming tasks such as trend analysis of old data or plotting new data as it arrives in real time.

The software is logically broken down into modules corresponding to functionality. Telemetry processing consists of buffering the data as it comes in through the serial port, decommutating a data packet, performing conversions of raw data into engineering units, and archiving both raw and converted data to disk (Figure 6.). The user is notified if any telemetry indicates an error condition.

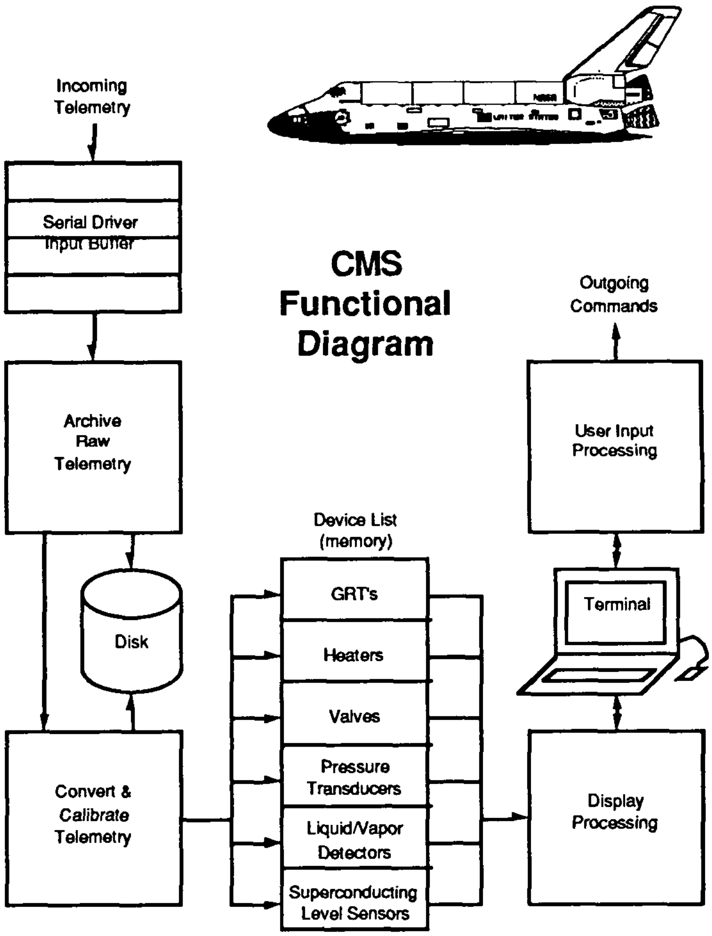


**Figure 6. Functional diagram of the ground based CMS software**

Command processing consists of a portion of the user interface to construct command packets and a command assembler which formats the packet for up-link and sends it out the serial port. Commanding can be automated for repetitive operations and a macro facility exists to simplify the creation of a packet.

Display processing is responsible for updating the screen and for changing display attributes. The telemetry being displayed is disjoint from telemetry processing so that old data may be viewed even if it is not present in the current down-link packet, new data is not necessarily being displayed, although it is still being checked for error conditions and archived. The display for a specific device is updated as new corresponding data comes in.

Each device may be individually selected for numerical display and a subset of all devices is always displayed graphically. Alerts and other error conditions are made known to the user in both the telemetry display window and a separate alert window. In addition an audible bell may sound if desired.

The user interface also allows general configuration of the system as well as facilities for performing utility functions such as heat pulse mass gauging or integrating the flow rate.

The development of the SHOOT Command and Monitoring System on a widely available and easy to use system, the Macintosh II, is proving to be both cost effective and efficient. The most important features are the point-and-click interface for interactive control and the reusable nature of the software.

## Conclusions

A knowledge-based approach facilitates the use of complex hardware by novice user. Point-and-click interfaces provide an expert user with powerful, intuitive, and flexible control over the same hardware. SHOOT represents the incorporation of these mature technologies into aerospace operations.

Superfluid Helium On-Orbit Transfer is a NASA Office of Space Flight Advanced Program Development Branch sponsored flight experiment managed by the Goddard Space Flight Center Cryogenics Technology Branch of the Engineering Directorate. The Ames Research Center Artificial Intelligence Research Branch of the Information Sciences Directorate is supporting GSFC by developing the software.

## References

Forgy, C.L. "On the Efficient Implementation of Production Systems", Ph.D. dissertation, Carnegie-Mellon University, 1974