CONF-820561--2

UCRL-86827

PREPRINT

UCRL--86827

DER2 015909

THE NOVA CONTROL SYSTEM: GOALS,
ARCHITECTURE, AND SYSTEM DESIGN

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This paper was prepared for submittal to
IFAC Workshop on Distributed
Computer Control Systems
Tallinn, Russia
May 24-26, 1982
May 19, 1982

MASTER

Lawrence
Livermore
National
Laboratory

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Abstract. The Nova laser fusion facility is presently under construction at LLNL. It is a large glass laser, generating 150 trillion watt pulses of infrared light at a wavelength of 1 micrometer (μ). Nova will achieve these energy levels using 10 amplifier chains, each focused onto fusion targets a few millimeters in diameter. Conversion of the 1 μ light to shorter wavelengths of 0.5 μ and 0.35 μ is expected to allow Nova to perform experiments in the physics regime of thermonuclear ignition.

The control system for the Nova laser must operate reliably in a harsh pulse power environment and satisfy requirements of technical functionality, flexibility, maintainability and operability. It is composed of four fundamental subsystems: Power Conditioning, Alignment, Laser-Diagnostics, and Target Diagnostics, together with a fifth, unifying subsystem called Central Controls. The system architecture utilizes a collection of distributed microcomputers, minicomputers, and components interconnected through high speed fiber optic communications systems.

The design objectives, development strategy and architecture of the overall control system and each of its four fundamental subsystems are discussed. Specific hardware and software developments in several areas are also covered.

*Work performed under the auspices of the U. S. Department of Energy by the Lawrence Livermore National Laboratory under Contract No. W-7405-ENG-48.

Keywords. Computer applications; computer control; data acquisition; digital systems; hierarchical systems; process control; programming languages.

INTRODUCTION

Nova is a 150 terawatt, ten arm laser fusion research facility currently under construction at the Lawrence Livermore National Laboratory (LLNL) (Simmons, 1982). As the world's most powerful glass laser system, Nova will provide researchers with an important new tool in the study of inertial confinement fusion (ICF). A principal objective of Nova is to demonstrate the feasibility of generating power from controlled thermonuclear reactions.

The predecessor to Nova was the highly successful, 30 terawatt, twenty arm infrared Shiva laser system (Fig. 1). It was the first large laser system at LLNL to employ a comprehensive computer based control and data acquisition system. The control system for Nova uses an evolutionary design based upon the proven Shiva control system (Suski, 1979).

Fig. 1. The twenty arm Shiva laser is Nova's predecessor.

An intermediate laser system called Novette is also under construction. It is scheduled for completion by early 1983 (approximately two years before Nova). Novette will utilize two beams and a control system of the Nova design to provide 30 TW of light on fusion targets. It will provide important data on laser operation and target performance in preparation for full scale Nova experiments.

The Nova system's ten laser beams will be capable of concentrating 100 to 150 kilojoules (kJ) in 3 nanosecond pulses of infrared light on a fusion target a few millimeters (mm) wide. The system also will generate light at shorter pulse lengths in power bursts up to 150 TW. Recent results have shown that shorter wavelength light is much more efficient at driving target implosions. Therefore, Nova will incorporate the ability to frequency double or triple its fundamental output, allowing target irradiation at 1.05 micrometers (μ) wavelength (infrared), 0.53 μ (green), or 0.35 μ (ultraviolet).

All arms of Nova must deliver their individual 15 kJ pulses to the target simultaneously (within ± 5 picoseconds). To achieve this objective, a single 100 microjoule pulse is selected from a train of such pulses. It is amplified to approximately 50 joules in a single pass through a nine stage preamplifier, and then it is split by partially reflecting mirrors into ten parallel chains of power amplifiers, each consisting of 15 cascaded laser amplifiers. Each pulse emerges from the output of its 180 meter long chain with a beam diameter of 74 centimeters. The pulses are subsequently reflected by large alignment mirrors, converted to shorter wavelengths, and finally focused onto a fusion target inside a 5 meter diameter aluminum vacuum vessel.

OVERVIEW

This paper will discuss the control system for Nova Fig. 2. First, the requirements and criteria established for the control system will be summarized to assist the reader in understanding the motivation for its design. A discussion of the architecture and commonly used components developed for the Nova Control System will then be presented. Applications of this system to achieve major control requirements conclude this paper.

Fig. 2. Nova is operated through hierarchical control system.

CONTROL REQUIREMENTS FOR NOVA

The Nova control system must satisfy control and data acquisition requirements in four fundamental areas:

Power Conditioning Subsystem

Functions. During a single laser "shot", over 60 megajoules of energy, stored in 25 kilovolt (kV) capacitor banks, is released through computer controlled ignitron switches to fire over 8600 flashlamps and 60 magnetic field devices. The discharge from the lamps imparts energy to neodymium doped glass rods and disks. This energy is released when infrared

(1.05 μ) light passes through the glass and is amplified. The magnetic field devices are called Faraday rotators. These devices use the transmission properties of paramagnetic glasses in intense magnetic fields to prevent reflected light from propagating in a reverse direction through the amplifiers which can cause component damage.

Requirements:

- Control of seven 1.5 megavolt-ampere (MVA) power supplies and twelve 100 kVA supplies.
- Firing of ignitrons to discharge capacitors with microsecond precision - switching 20 to 30 megamps in 1 ms.
- Generation of triggers to synchronize diagnostics and components.
- Monitoring of safety and abort systems.
- Acquisition and analysis of current waveforms and the actual firing sequence.

Alignment Subsystem

Functions. The light pulses travel approximately 250 meters from the point of origination until target impact. Along this path, there are four principal locations where the pulsed beam is turned, pointed, centered, divided, expanded, focused, and diagnosed. These are the Master Oscillator where the initial pulse is formed, the Splitter Array where the pulse is divided into 10 paths, the Amplifier Chains where the pulsed beams are amplified and expanded, and the Output/Target Area where the beams are aimed and focused on the target. Alignment sensors generate video images of beam positions and profiles by viewing light split off from the main paths with partially transmitting mirrors or partially reflectory optics. Charge coupled device arrays (CCD's) are used to convert the beam information to video information which can be viewed on black-and-white television monitors, or digitized for computer analysis.

Requirements:

- Local and remote control of more than 1000 stepping motors to manipulate mirrors, lenses, shutters, and other alignment components at rates up to 300 steps/second (Nova standard) and, in a few cases, 5000 steps/second.
- Perform automatic alignment of the main oscillator, splitter arrays and amplifier chain components.
- Record alignment configurations for subsequent re-use and analysis.

Laser Diagnostics Subsystem

Functions. Accurate characterizations of beam quality, energy, and temporal properties are required at key locations throughout the laser system to interpret target results. Such measurements also aid in preventing damage to laser components due to excessive energy densities.

Laser energies ranging from 70 joules (J) to 10 kJ and time durations ranging from 100 picoseconds (ps) to 10 nanoseconds (ns) must be diagnosed. Beam characterization utilizes absorbing glass calorimetry and high speed photodiode detectors to measure energy. Transient digitizers and streak cameras record time discrimination. Digital solid state memories attached to CCD based video sensors capture and store pulsed images.

Requirements:

- Setup, control, and acquisition of data from approximately 100 sensors producing over 300,000 bytes of data for each laser shot.
- Acquisition of 160,000 bytes of data from several digital memories attached to streak cameras in distributed locations.
- Post shot storage, display, and analysis of results.

Target Subsystems

Function. Over 120 instruments acquire data on a single shot to characterize the results of the target implosion. A large portion of this data is collected as temporally resolving waveforms using transient digitizers and high speed streak cameras. Diagnostics include x-ray and particle detectors, calorimeters, photodiodes, photomultipliers and other instruments with resolutions ranging from 10 picoseconds to several seconds. The target system requires extensive reconfiguration of instruments, their sensitivities and triggering specifications, between successive target shots. The target chamber and several diagnostic instruments are serviced by individual vacuum systems. These require interlocked operation to prevent incorrect configurations of their more than 500 valves, leak detectors, and pressure detectors.

Requirements:

- Setup, control and acquisition for approximately 120 instruments generating a total of 10^7 bytes of data.
- Maintenance of vacuum integrity through interlocked control of valves according to known permissible configurations and pressure sensor readings.
- Support of major reconfigurations of diagnostics instruments between target shots.

DESIGN OBJECTIVES

In addition to the fundamental requirements summarized above, two additional objectives motivated the design of the Nova Control System:

- Reduction of development and long-term maintenance costs by employing a consistent overall architecture and a set of common components.
- Ensuring the flexibility required to optimize designs according to the unique requirements of the individual subsystems.

DESIGN CRITERIA

The design criteria established for the Nova Control System are representative of those found in large distributed control systems of this type. In addition to the primary criterion of cost, principal criteria include:

Reliability. The precise specification of reliability for control systems such as Nova's can be elusive. When matters of personnel safety are not involved, reliability criteria are often subordinate to other performance goals and cost constraints. However, two criteria were clearly established for Nova.

The control system must function normally in the high voltage, high current pulsed power environment which generates harsh electromagnetic interference (EMI) conditions. In addition, no single point failure of the control system should preclude overall operation of the laser system. (Manual or reduced levels of automated control are acceptable.)

Adaptability. Requirements evolve as Nova nears its final stage of construction, and will continue to evolve through the years of its operation. The control system must be adaptable to changes and extensions to the laser system configuration and its operational needs.

Performance. Simply stated, control system performance (speed and functionality) should not constrain the shot rate of the laser.

NOVA CONTROL SYSTEM DESIGN

Functional Organization. Nova's control system employs a distributed, computer based architecture which evolved from the successful Shiva laser control system. It is organized functionally according to the four fundamental subsystems; Power Conditioning, Alignment, Laser Diagnostics, and Target Diagnostics. A fifth, unifying subsystem called Central Controls centralizes, augments, and coordinates the other subsystems' functions (Fig. 3). The criteria of reliability and adaptability are met by the computer based, extendible nature of the system. The flexibility required to optimize individual subsystem architectures is provided by the inclusion of the Central Control subsystem. It establishes a single point at which compatible interfaces for command, control, and data interactions are established.

Fig. 3. A single subsystem integrates and centralizes distributed functions.

Development Strategy. The development strategy for the Nova control system capitalizes on the distinction between subsystems to accelerate the implementation cycle. The development teams are organized according to the five subsystems. Initial effort concentrated on the development of common products and techniques which would later be employed across the four functional subsystems. Developers of these products subsequently migrated into lead roles in the subsystems which employ those "tools". This reduced the need for a separate team of developers, and simplified the task of technology transfer into the subsystem efforts. Actual subsystem development was organized according to the following guidelines:

- **Parallel Groups** - The development efforts for the four fundamental subsystems proceeded in parallel using four distinct teams.
- **Common Products** - The products acquired and developed for common functions became resources in the development and integration of the subsystems.
- **Central Support** - A central facility, supported by a VAX-11/780, provided a central, well maintained, resource for software development and global system information.
- **Distributed Testing** - Hardware and software particular to each subsystem are tested in distributed locations configured with appropriate facilities. This has reduced unnecessary interference between the subsystems, resulting in an acceleration of the total development effort.

A Distributed Control System. In this hierarchically structured system approximately 50 Digital Equipment Corporation (DEC) LSI-11/23 microcomputers provide localized control and data acquisition capabilities in geographically distributed locations throughout the laser fusion facility. Data from these front end processors (FEP's) is

collected, analyzed and integrated at the Central Control level with three redundant Digital Equipment Corporation VAX-11/780's minicomputers. Remote command and control capabilities, higher level control functions (e.g., automatic laser alignment), and high volume data storage and manipulation, are implemented at this level.

The physical distance between devices to be controlled suggests a distributed architecture. However, there are additional factors motivating the use of distributed microcomputers for device control:

- The real time nature of device control establishes requirements for computer interrupt handling capacity, low level device polling, and fast responses to simple control and status inputs. It is inappropriate, from a cost and performance perspective, to meet these needs in large central computer.
- A requirement for simple device control capabilities located physically nearby is efficiently achieved by providing the locally situated microcomputers with attached control panels.
- Device control can be optimized through individual microcomputer configurations which are not constrained by the requirements of unrelated devices.
- Independent local control functionality supports individual device maintenance while the remainder of the control system remains operational.

The large central minicomputers in Nova support control functions which cannot be effectively implemented in the distributed microcomputers due to cost considerations or technical constraints. For example, the design of the central controls architecture was strongly influenced by the need to perform alignment of over 230 laser components utilizing video images from 55 distributed sensor locations. Replicating expensive video processing capabilities at several locations is not cost effective. Therefore, automatic alignment functions are concentrated in the central computers which can efficiently support this speed and memory intensive task.

Development and Off-Line Analysis Support. The development and operation of a computer based control system are incompatible tasks for a single shared resource computer. Experience with the Shiva system indicated that a computer system configured and optimized to perform continuous control activities could not give adequate service to developers. For example, the need to provide high availability of operational controls precludes all but intermittent testing activities. In addition, software development activities such as editing and compilation significantly deteriorate control system performance.

In order to maintain high development and maintenance productivity, a separate system was established for Nova on which software and hardware development activities could occur without interfering with normal

control system operations. This computer system is configured with several access terminals, a large volume of mass storage, a variety of analysis software, and specialized output devices (e.g., graphic hardcopy units).

This computer is connected into the control system network. This feature allows experimental data to be transferred to it for long-term analysis and storage, an important requirement for successful Nova operation. Large data bases used intermittently by the control system, such as the relatively static system configuration information, are also maintained on this system.

Development Strategy. The general architecture of the control system was established early in the Nova project, necessarily in advance of final specifications for the four fundamental subsystems. Early development, therefore, concentrated on developing the set of hardware and software packages which would be used to construct, support, and integrate the subsystems.

The next portion of this paper discusses the central architecture of the control system and packages developed for common uses. The distinct subsystem architectures which employ these tools to suit their individual requirements are then described.

CONTROL SYSTEM ARCHITECTURE

The hardware architecture of the Nova Control System is illustrated in Fig. 4. The LSI-11/23 microcomputers communicate to each other, to remote devices such as CCD cameras, and to the three VAX-11/780's primarily via fiber optic communications links. Command and control information flows from the central computers into the distributed controllers and devices, with status and data typically returning. The VAX-11/780's are configured with four megabytes of local memory each, plus approximately two megabytes of shared memory. Attached to the central computers is a high speed array processor and a video digitizer. This package can analyze images from any of the video-based sensors by utilizing a computer controlled video switching network. Typically, the three central computers share tasks to provide a satisfactory performance level, but the system can be operated at reduced performance levels from a single VAX-11/780 if necessary. Four fully programmable operator consoles provide central control capabilities to any of the four subsystems. An Event Logger implemented on separate computer maintains a time annotated record of important control system actions.

Central Operator Consoles. The principal operator interface to Nova is provided through four, fully programmable central operator consoles. The design for each console (see Fig. 5 and 6) is optimized for use by a single person who can view status and initiate control functions for any of the four fundamental control subsystems. Three mid-resolution (512 x 640) 19" color displays are driven by a Rantek RM9400 graphics controller. Two peripheral displays provide status information. A

Fig. 4. The Nova control system hardware architecture.

Fig. 5. The Nova central operator console.

Fig. 6. Operator console I/O system.

centrally mounted third screen displays operator command templates. It is overlaid with a transparent touch panel which translates operator selections into screen coordinates. The touch panel is augmented by a force operated joystick for stepping motor control and a numeric keyboard for data entry.

A software package treats each console as an integral control unit. This package supports the graphical display of control system elements as "entities" which may be selected via the touch panel to indicate control commands. Alternatively, shapes or colors can be changed via an executing program to indicate status. Designed to be control system oriented, this package has two important characteristics:

- High performance - Operator selections are immediately acknowledged. Screen updates lag data by less than 0.2 seconds.
- Control Oriented Programming - Engineering users prefer to program control system functions as opposed to writing computer graphics software. Therefore, the software interface to the operator console

allows reference to names and functions of control system elements in preference to details of screen coordinates and graphics controller characteristics.

This high performance package for on-line control applications is augmented by general purpose graphics packages (Brown, 1981) to satisfy requirements of lower performance but higher functionality in post shot data display and analysis.

Image Processing. The control system must be capable of analyzing video beam images generated by alignment system cameras once every one to three seconds. These analyses determine 1) the center coordinates of softfocused, noisy, laser beam profiles and 2) the offsets between diffraction patterns of overlapped alignment cross hairs. The VAX-11/780, with its virtual memory capability, provides the address space required for complex image analysis. It is augmented by a high speed auxiliary image processing system. This consists of a Quantex video frame digitizer with 256 x 256 addressability interfaced directly to a Floating Point System FPS-120B array processor. The array processor is interfaced to a central VAX-11/780 computer through its I/O bus (UNIBUS). This auxiliary system increases the speed of image processing by a factor of 100, allowing closed loop image analyses for the entire facility to be performed by a single set of hardware. Video sensor images to be analyzed are selected through a computer controlled video switching system.

Support of Distributed Communications

In a distributed computer control system (DCCS), well-defined methods for communicating commands, status, data and synchronization between computers, devices, and software processes are required. The performance of the communications media, as measured by computer loading and speed of transfer, should not constrain the control system's ability to service the facility. In addition, restrictions on data format and content must be minimized. These latter criteria are motivated by the concept that the general purpose "tools" of the control system developers should enhance, not hinder, their ability to meet their objectives. Nova uses shared memory and fiber optic transmission links to satisfy such communications requirements.

Shared Memory. Communication between processes residing in the same or physically adjacent computers in Nova employs shared data structures in commonly accessible memory. This technique is particularly well suited to providing identical status information to more than one process at a given instant. The use of shared memory on an extensive basis across control subsystems yields data flow and access paths similar to those encountered in distributed point-to-point computer networks. Management of shared data structures, access control, and a "network analyzer" utility to assist in diagnosing communications activity in shared memory are provided by a software package called NSM (Network Shared Memory). NSM supports management of common data structures across subsystems, labels collections of these structures (called "tables"), sets up access

control (Read, Modify, Write) on a per program basis, provides the semaphores necessary to interlock table updates, and signals suspended processes when table changes occur. NSM minimizes process overhead while waiting for data changes. It also improves the maintainability of the control system by managing the topology of the shared memory network.

Novanet. The primary medium for distributing command, status, and control information to remotely located computers is the Novanet fiber optic communications system. A collection of intelligent network hardware devices (Novalink) provides network functionality up through the Physical, Data Link, and Network Layers (including routing) as described in the ISO OSI reference model for Open System's Interconnections (Tanenbaum, 1981). Software supports the required functions of the Transport and Session Layers (blocking/deblocking and process to process connections).

The objective of the Novanet development effort was to provide a high performance method of interconnecting computers with computers as well as computers with devices. This combination is an intriguing feature in control systems since it implies that any computer in the OCCS network may access any device (such as a remote digital image memory) connected into the network. This results in simplified programming, more flexibility in architecture, cost reductions, and higher performance by the elimination of intermediate processors.

Principal characteristics of Novanet are:

- 10⁷ bits/second using fiber optics.
- Devices connect directly into network.
- Node to node routing under hardware control.
- Assignment of network mastership to nodes under hardware control.
- Asynchronous word and block transfers.
- Word by word error checking and transfer acknowledgements performed by hardware.
- Network dynamically segmented into subnetworks to increase total available bandwidth.

The Novanet protocol (Fig. 7) employs a 50 bit serial packet to transfer data, assign network mastership, and send control information to the network interfaces. Each packet is acknowledged by the receiving node's hardware. Control of network mastership is via token passing. Several modules comprise the Novanet support hardware. A Master/Slave Controller (MSC) plugs directly into a computer bus. The MSC utilizes microprogrammed state machine control to implement data serialization, data verification, arbitration of network mastership, and direct memory access (DMA) transfers to and from computer memory. A Multiple Device

Novalink hardware provides

- Routing (address)
- Error detection (CRC)
- Multiple functionality (preamble)
- Reproduces Q-bus remotely
- Direct access to Q-bus addresses
- Reply to each packet
- Transfer is by direct memory access (DMA)
- Error counters

Fig. 7. Novalink serial packet.

Interface (MDI) is used to connect remote digital image memories directly into the Novanet network. MDI's operating in slave mode to MSC's can transfer 160,000 bytes of image memory in approximately 2 seconds. The Q-bus Device Interface (QBDI) is functional similar to the MDI, but provides an LSI-11 bus (Q-bus) compatible connection to the network. Programmed operation, DMA, and interrupt functions of standard Q-bus interfaces are supported.

The central communications element for the network is the Node Star (Fig. 8).

Fig. 8. Novanet connects devices and computers.

This unit broadcasts incoming data to all processor and device nodes, exclusive of the originator. The Node Star converts the network, which consists of physical point-to-point fiber optic connections, to a logical "bus". The use of the Node Star was motivated by limitations in the number of fiber optic "taps" allowed in multi-drop systems. It has the ability to segment the network into distinct subnetworks during high volume data flow conditions. Configured as a collection of smaller Node

Stars which are selectively coupled together under program control, a single point failure in the Node Star will affect only a small subset of the network nodes. Up to 64 subnetworks can be created in a 256 node Novanet system. The Node Star also provides self-diagnosis capability for Novanet by supporting detection and isolation of faulty nodes. The final element of Novanet hardware, a network analyzer, captures and displays selected network traffic as a diagnostic aid for hardware and software.

Novabus. Several tasks in Nova require relatively simple device control functions, but must be closely synchronized at shot time. Many of these functions, such as ignitron firing and interlock sensing, are associated with the Power Conditioning subsystem. Another such function is providing of preshot triggers to the diagnostics subsystems. The Novabus system was developed to provide a fiber optic based communications link, driven from a central FEP, for these functions. Novabus uses the same fiber optic technology as Novanet, but utilizes a simplified protocol (Fig. 9) optimized for device control from a single bus master.

Fig. 9. Novabus serial packet.

The principal hardware modules in the Novabus system include the Fiber Interface Controller, which connects to the LSI-11 Q-bus, a Node Star capable of accommodating sixteen lines, and a Node Drop for each group of physically local devices to be connected to the fiber bus. Each Node Drop supports connection of devices to the network using a standardized bus which is logically similar to the Q-bus. In addition, it repeats the optical signal to allow chaining of Node Drops in series. All 110 drops in Nova are contained within twelve such chains. Novabus is implemented redundantly, with each device serviced by two distinct Novabus systems. This architecture increases reliability and availability. In addition, when both Novabus systems are fully operational, control functions are shared in order to improve control system performance.

Event Logging. A DCCS typically will have many functions operating concurrently. An important method of tracking operations activity, and analyzing the cause and effect of control system malfunctions, is examination of an event log. An event, in this sense, is an action or status change which has significance at the operational level. Examples in Nova include operator activation of an alignment control sequence, the

completion of a remote mirror gimbal motion, and the opening of a safety interlock. For Nova a prototype event logging facility, employing a DEC PDP-11/34 mini-computer, has been connected via Novalink and multi-port memories to the control system. It provides an independent station at which significant, time stamped control system events can be displayed and stored.

Praxis: A Language for Control Systems Implementation. The maintainability of a DCCS is dependent on the standardization and documentation of its hardware and software components. Techniques for achieving these characteristics in hardware are well known and established. In software, maintainability is affected by its readability - the clarity with which the source statements represent their function. In a large DCCS effort, techniques to assist the software engineer in ensuring compatibility between interdependent modules and data structures are also required. The ADA programming language development effort, sponsored by the United States Department of Defense, is attempting to achieve this and other goals in control system applications. The Nova project, through the Department of Energy, has fostered the development of the Praxis language (Evans, 1981) to achieve some essential goals of ADA on a schedule useful to the Nova project.

Praxis is a modern, high-level computer language designed for the efficient programming of control systems applications. It is a strongly typed, block structured language in the tradition of Pascal, with much of the power of the forthcoming ADA. It supports the development of software composed of separately compiled modules, user defined data types, exception handling, detailed control mechanisms, and encapsulated data and routines. Direct access to computer facilities, efficient bit manipulation, and interlocked access to critical regions are provided.

Praxis contains high-level constructs which enhance readability and portability in control system applications. It also allows controlled access to machine dependencies, enabling the use of high performance, realtime control capabilities specific to a particular computer architecture. Praxis supports separate compilation of modules while enforcing strong data type checking between such modules at compile time. This reduces the time necessary to debug software at execution time.

The Praxis compiler is written in the Praxis language. It executes under the VAX/VMS and RSX-11/M operating systems, generating optimized code for VAX's, PDP-11's, and LSI-11's. Over 150,000 lines of Praxis source code now exist in the Nova control system. An example of a Praxis language interrupt driven clock routine for the LSI-11/23 is found in Fig. 10.

Configuration Management. In the development of a DCCS, two types of configuration management must be addressed, management of software configuration and management of control system configuration. The primary objective in software configuration management is to maintain multiple versions of software modules. This allows establishment of working "baselines" and revision levels which ensure access to proven

```

Declare
  Vector is structure
    Routine : interrupt procedure () initially service
    Status  : logical initially 8#340
Endstructure

  Clock   : volatile location (8!100) vector
  Ticks   : static integer initially 0

Enddeclare

Interrupt procedure service ()
  Ticks *= +1

Endprocedure [service] ()

```

Fig. 10. A Praxis interrupt driver clock routine.

software while development continues. The need for this capability increases with the number of developers in a DCCS. Nova uses the standard VAX-11/780 file directory system to maintain software revisions from the initial development to the on-line stages. A software librarian has responsibility for maintaining quality assurance and baseline control. In general, a more flexible software library system is desirable, but until recently, has not been commercially available for the VAX-11/780.

The second category, management of the control system hardware configuration, is required to assist in its operation and maintenance. In particular, device data which changes frequently must be easily accessible and modified. Such data includes the network configuration, predefined configurations of laser system components, and predefined sequences of operations. The principal support for such functions is provided by a vendor supplied relational data base system (RDB) for the VAX-11/780 named Oracle (Oracle, 1981). RDB's prove well suited to DCCS applications. Flexibility in the control system software is frequently gained through functions driven by tables, which can correspond directly to equivalent tables in an RDB.

THE SUBSYSTEM ARCHITECTURES

The four fundamental subsystems which employ these and other common components, have each developed architectures uniquely suited to their requirements (previously summarized). These architectures are now examined.

Power Conditioning. The Power Conditioning subsystem must perform short programmable sequences of low-level command and control for several hundred distributed devices at precisely spaced intervals to microsecond accuracy. One method of achieving this capability is to connect all devices to the I/O bus of single microcomputer, such as an LSI-11/23 FEP. This simplifies the task of synchronizing control sequences.

However, the devices to be controlled are in geographically distributed locations in harsh EMI environments. The solution chosen in this subsystem was to extend the LSI-11/23's I/O bus using the high speed fiber optic Novabus, developed specifically for this application. All devices in the Power Conditioning system are controllable from either of two redundant LSI-11/Novabus systems to provide fault tolerance.

Timed control sequences are maintained in multi-port memories which connect the two Novabus FEP's to the central VAX-11/780's. A third interconnected LSI-11 supports a separate maintenance control console which can, if necessary, complete a full system shot sequence independent of the central subsystem.

Several standardized interfaces for device control at each drop on the Novabus are used. For example, the Capacitor Bank Interface fires high voltage ignitrons at precise intervals using an on-board timer triggered over Novabus. The Interlocks Interface provides the ability to monitor the hardwired, triply redundant, safety interlock system. The Power Supply Interface controls and monitors the megavolt-ampere power supplies which charge the capacitor bank.

Software in the Power Conditioning subsystem is functionally balanced between the central computer and its FEP's (Fig. 11). An operator interacts with the central computers through a series of menus on the central operator console. The central computers respond by placing commands for control devices in the memory shared with the FEP's.

Fig. 11. Dual Novabus application in Power Conditioning subsystem.

Alternatively, commands can originate from two centrally resident programs; the shot scheduler program controls events during shot preparation and the sequencer program completes the time critical firing of the system. Actions initiated at the operator console can result in the loading of a shot "configuration", including voltage levels, timing information, and device selections, from a RDB. The FEP's route those commands to the remote hardware through Novabus, and regularly poll this hardware to update a status table in shared memory. The control computer

thus has visibility of the system status at all times. FEP's also log changing status data at very high rates to provide a history of voltage levels and actions in the seconds prior to and immediately after a system shot.

Alignment Control. Approximately twenty-three LSI-11/23 based stepping motors controllers (SMC's) are used to control movable alignment subsystem components driven by nearly 1000 stepping motors. The Nova SMC's provide substantial functionality at each location:

- Variable rate control of 60 stepping motors.
- A programmable alphanumeric control panel.
- Programmable backlash correction.
- Crosscoupled control of beam pointing and centering devices.
- Support of optical position encoders.
- Connection via Novanet to the central control subsystem.

SMC's provides device oriented (as opposed to motor oriented) command and control functionality. For example, a lens mounted on a three axis, three motor gimbal is treated as a single controllable device. Predefined combinations of device positions, referred to as configurations, are loaded into the SMC's through Novanet. These configurations are maintained in a central RDB which can be updated by operations personnel.

Automatic laser alignment, crucial to maintaining a high shot rate, is performed by software resident in the central computers. Position information (derived using beam image analysis) is translated into correcting stepping motor commands, which are sent to the SMC's through Novanet (Fig. 12).

Fig. 12. Automatic alignment through image analysis.

Laser Diagnostics. This subsystem (Czarski, 1981) acquires, centralizes, and analyzes over 200 simultaneous measurements at shot time. Three distinct classes of devices are serviced. Very high speed transients recorded by digital streak cameras are stored in distributed locations in 160,000 byte digital memories. Arrays of data from transient digitizers (~2000 bytes each) and small quantities of data from single value, time varying detectors (e.g., photodiodes and calorimeters) are also processed. The large volume of data produced by the streak cameras and transient digitizers precludes economical processing in local FEP's. Therefore, the streak cameras connect directly in Novanet using MDI's. Transient digitizers connect to Novanet through IEEE-488 interfaces connected to QBDI's. Data from these devices is transferred directly into the high capacity central control computers for storage and analysis. Data can be retained in the digital memories of each device until the central system acquires it.

Six FEP's are used to process the low volume data. As in the Alignment subsystem, substantial local control capability is provided. A typical FEP (Fig. 17) contains sufficient logic to support it as a 128 kiloword microcomputer, communication hardware for extended triggers and Novalink, interfaces for optional local terminals and floppy discs and command and control logic for its diagnostics sensors.

The flexibility afforded the subsystem designer to reduce cost and optimize control via the FEP's is shown here in the Data Interconnect and Power Distribution (DIAD) system. A controller connects the FEP to the DIAD which in turn distributes commands and collects data from up to 20 separate sensors. Up to three DIADs may be connected to an FEP. Communication between sensors, DIADs, and the FEP is over 125 kilobit/sec., optically isolated lines.

Each sensor may have associated variable gain amplifiers configured with shot dependent parameters. These configurations, stored on a RDB in the central computers, are transmitted to the amplifiers through Novanet and the FEP.

Target Controls. The Nova target diagnostics system (Fig. 14) must uniquely configure over 100 diagnostic instruments which characterize target performance on each shot. Widely varying signal levels and bandwidths dictate a flexible subsystem architecture which carefully treats issues such as instrument isolation, grounding, crosstalk prevention, and signal degradation. To assist in meeting these requirements, all target diagnostics sensors interface through CAMAC (CAEC, 1972) equipment. Geographically distributed FEP's minimize analog signal cable lengths to maximize the signal quality.

Optically isolated, single screen extensions of the Nova operator consoles provide local control capability identical to that available in the central control room. Since the technology used for control is identical, only a single set of hardware and software for both local and remote control is required.

Fig. 13. LSI-11 based laser data acquisition unit.

Fig. 14. Nova's target subsystem allows frequent instrument reconfiguration.

A diagnostic station comprises an electrically isolated group of racks, at least one FEP, at least one CAMAC crate (CAMAC bus and module rack), and the digitizers and equipment required to support an associated diagnostic detector. Supported through the CAMAC system are transient digitizers, charge integrators, calorimeters, and high voltage diagnostic power supplies.

Instrument locations, calibrations, and gains used by the FEP are stored in a central computer RDB. Analysis of the one megabyte of data acquired on a single shot requires this configuration information. Therefore, after each shot, a single data base consisting of both raw data and instrument configurations is created and stored for subsequent long-term analysis.

Subsystem Synchronization. The use of a DCCS for a facility such as Nova requires methods for synchronizing distributed control activities to varying tolerances. Requirements on flexibility, accuracy, and speed of synchronization directly affect its cost. Nova synchronization utilizes two hardware systems augmented by software to support the changing balance of requirements between flexibility and accuracy as shot time is neared.

Until one minute before a target shot, most synchronization is accomplished through operator and software communication. During the time the banks begin to charge until 10 ms. prior to the shot, devices are triggered over the Novabus to an accuracy of ± 200 sec. During this time the Power Conditioning FEP's are dedicated to executing the sequencer script and checking for abort status conditions. At 10 ns. prior to the shot, a universal trigger is broadcast over Novabus to preset timers. These timers deliver synchronization signals accurate within $\pm .5$ sec. to arm diagnostics and fire the ignitrons. At 1 sec. prior to pulse propagation, the final timer starts the Fast Timing Control system to generate up to 128 programmable triggers with ± 1 ns. precision. These triggers are propagated over metallic wires or fiber optics according to their destination.

CONCLUSIONS

Multi-level control systems can utilize microcomputers as front end processors to provide low level local control and acquisition functions while larger mini-computers provide centralization and high level control functions. The development philosophy of using parallel teams to develop controls for parallel subsystems has been an effective approach in Nova and the preceding Shiva system. Development and inter-subsystem compatibility is enhanced by having a large central facility to support software development across subsystems. The goal of an integrated command, control, and data acquisition system is realizable by establishing a central subsystem with which the fundamental control subsystems interact. Subsystem synchronization needs, however, may require more direct paths for integration. These requirements can be satisfied in a manner consistent with the overall system architecture.

SUMMARY

The control system for Nova meets several criteria, in particular flexibility and reliability, through the use of a distributed computer based control system. The system is organized into a hierarchy of computers grouped according to the four fundamental control and data acquisition tasks for Nova. The flexibility to optimize control subsystem architectures for individual requirements has resulted in four relatively distinct and innovative architectures. A fifth, unifying subsystem is utilized to integrate and centralize control functions. A high degree of programmability, extending from low level microcomputer up through the central operator consoles, ensures the ability to meet new control system requirements as they are identified. The control system survives the intense EMI environment of NOVA through the use of fiber optic isolation, careful grounding and shielding, and fault tolerant designs.

ACKNOWLEDGEMENTS

In addition to the authors, a number of people have contributed substantially to the Nova Control system effort. L. Berkbigler developed the Novabus system; R. Calliger and D. Kroepfle helped to develop the target systems; D. Christie developed the safety interlock system; T. DeGroot and J. Smart developed the power conditioning software; J. R. Greenwood led the Praxis effort with BBN, Inc.; J. R. Hill was responsible for the Novanet software; C. Humphreys developed the image processing system; D. McGuigan has led the relational data base efforts; D. Myers developed the laser diagnostics acquisition hardware; J. Oicles led the synchronization system design; S. Ruddock developed the Node Star for Novanet; J. Wilkerson has developed much of the console and laser diagnostics software; and G. Aune and T. Lynch of Digital Equipment Corporation have contributed substantially to our understanding and effective use of VAX/VMS. The authors also wish to acknowledge the consistent support of J. Holzrichter, beneficial criticism of R. Godwin, and the technical guidance of W. Simmons. The patience of C. Gardner in preparing this manuscript is gratefully noted.

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