Design and Implementation of the OMEGA Power Conditioning Executive

A significant amount of hardware was added to OMEGA to upgrade it to a 30-kJ, 60-beam laser. To control this hardware, an entirely new control system was implemented. This article describes one of the core subsystems of that control system—the Power Conditioning Executive.[1] Timing and control of the electrical energy fed to OMEGA's amplifiers are provided by the power conditioning system comprising state-of-the-art, high-power electrical switching components that are centrally controlled by a workstation linked to distributed sets of 218 embedded processors, one per amplifier. In this article we review this important subsystem of the OMEGA control system, beginning with a "black box" view of its role in the overall control system and proceeding with an in-depth review of the subsystem itself and its major components.

Laser Control System Overview

The OMEGA laser control system is an entirely new design, based in part on the previous OMEGA system in terms of overall requirements and system concepts. The new system makes use of both centralized and distributed control concepts. Central control is provided by a series of Sun SPARC workstations, each running an individual "executive" process that controls one aspect of the laser or diagnostic subsystems.

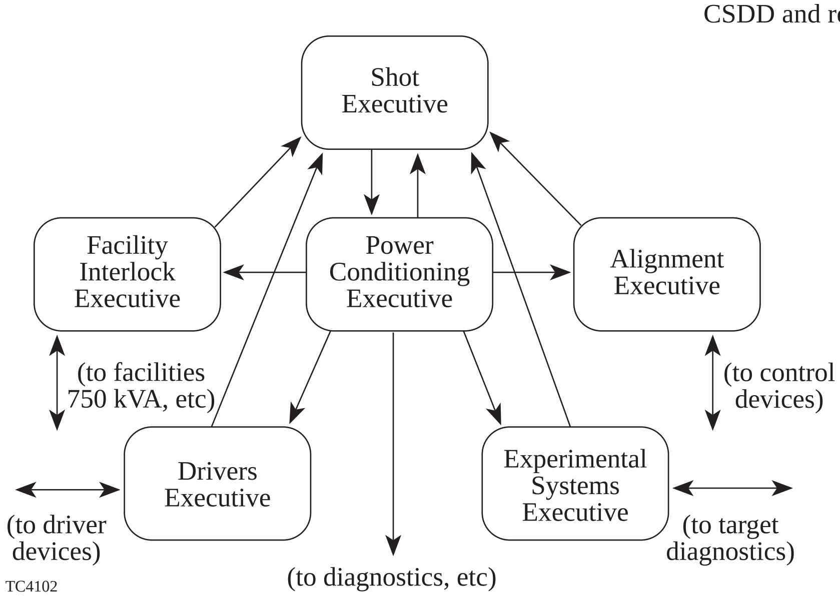

Figure 65.26
The laser control system is distributed over several *executives* that are interconnected via Ethernet using TCP/IP. Each executive performs or oversees one aspect of the laser operation and interacts with its associated devices.

As shown in Fig. 65.26, the primary executives are Power Conditioning, Alignment, Shot Supervisor, Facility Interlock, Laser Drivers, and Experimental (target irradiation and fusion diagnostics). Executive processes are interconnected via Ethernet using TCP/IP.[2] In the following sections, we will describe the power conditioning subsystem (Fig. 65.27), while a future article will review the entire control system design. Additional design details are available in the OMEGA Control System Design Document (CSDD)[3] and the OMEGA System Operations Manual.[4]

Power Conditioning Subsystem

As illustrated in Fig. 65.28, the power conditioning subsystem is organized vertically into the following components: executive [Graphical User Interface (GUI), state engine, status display, timing interface, etc.], local operating network (LON)/LON to Ethernet network adaptor (LON/LENA) interface, power conditioning modules (PCM's). The PCM's are the main control interface to the power conditioning units (PCU's), which contain the pulse-forming networks that supply electrical energy to the laser amplifiers. This article discusses the control software for this portion of the system. For details of the timing system, the PCU's, or the PCM's, consult the CSDD and related design documents.[5–7]

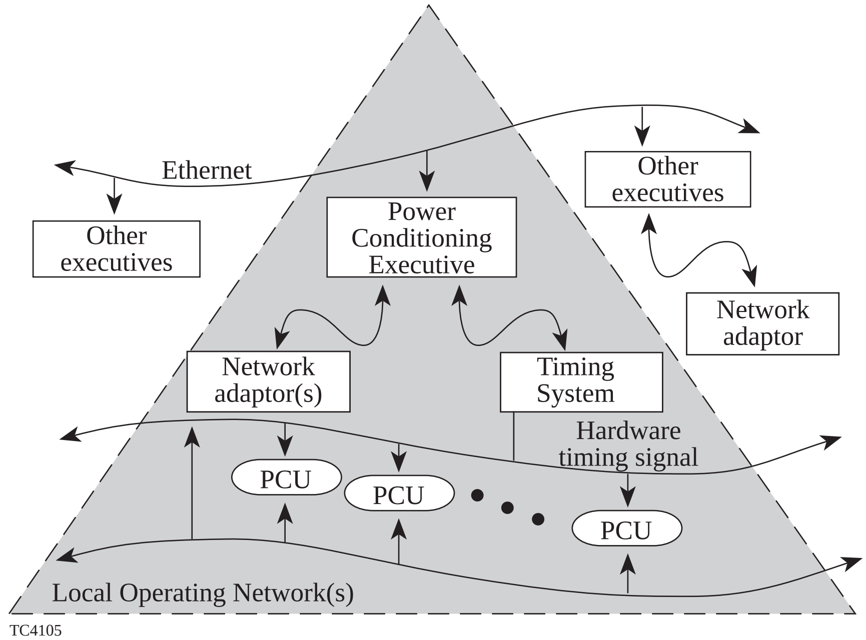

Figure 65.27
Power conditioning is one subsystem of the OMEGA laser control system. It operates as a unit to control individual power conditioning units (PCU's) but also interacts with the other OMEGA executives via Ethernet communication.

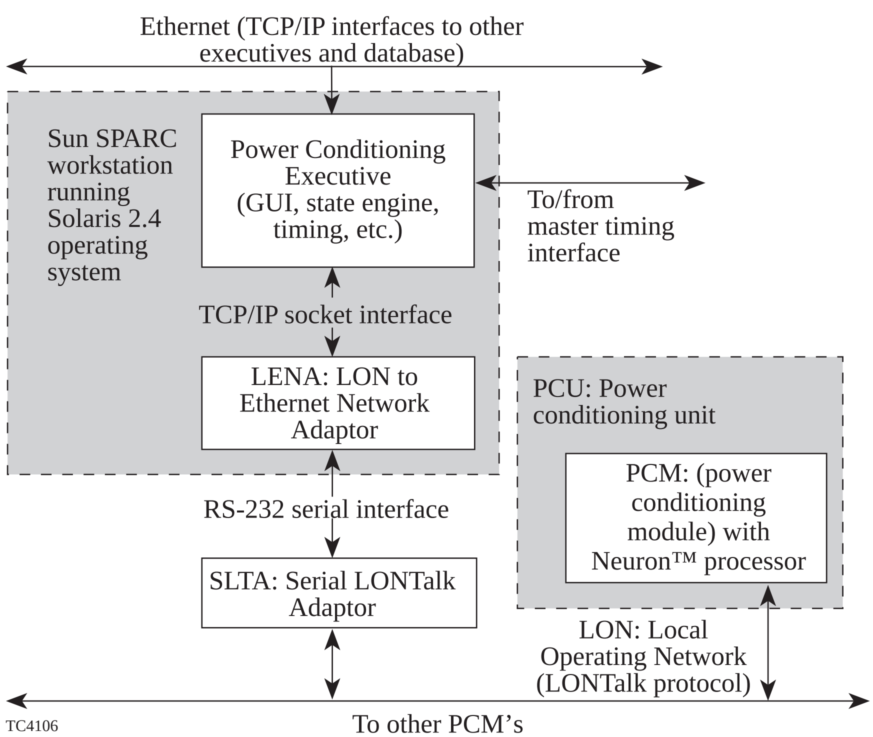

Figure 65.28
The power conditioning subsystem is distributed vertically into executive, mid-level, and low-level processors. This organization facilitates both modular code development and reusability. The local operating network (LON) is a proprietary network (hardware and protocol) that connects the Neuron™-based power conditioning modules (PCM's) to the executive via the mid-level processors (LENA's and SLTA's). Each LENA/SLTA combination provides access to up to 40 PCM's.

1. Power Conditioning Executive (PCE)

In addition to providing the central control for power conditioning, the Power Conditioning Executive (PCE) subsystem also establishes and implements the "shot sequence" for the entire laser system. As shown in Fig. 65.29, this subsystem comprises several interconnected subprocesses whose functions are to operate the laser in a safe and predictable manner.[8] These subprocesses all run on a single multiprocessor Sun SPARC workstation under the Solaris 2.4 operating system. The majority of the code was developed using the C++ object-oriented programming language,[9] though some subprocesses and libraries were developed using ANSI standard C[10] for convenience in device interfacing or reusability. In addition, the PCE has an X-based status display that was developed using low-level X libraries for optimal display speed.

The Graphical User Interface is a separate process, written in C, utilizing the UIM/X Graphical User Interface builder to construct the X/Motif interface. It will be discussed in a later section.

a. State engine. The heart of the PCE is a general-purpose state engine that is programmed with the transition network illustrated in Fig. 65.30. The transitions are caused by messages that can be received from the user interface, another executive, or the PCE itself, in the case of *automatic* (self-initiated) transitions.[11] For speed and simplicity, the state and transition lists are stored in fixed-size arrays rather than linked lists. This state engine has been generalized for reuse in the other executives.

b. Message queue. The messages that cause state transitions in the PCE are generally queued in a first-in first-out (FIFO) message queue that operates asynchronously with the state engine. An exception is made for abort messages, which cause all pending messages to be dequeued, thus placing the abort at the head of the queue for immediate processing. The message-queue subprocess has also been generalized into a library for reuse in other executives. It includes both a simple command line and a text-based interface for use with the independent GUI process.

c. Status display. Amplifier status information can be displayed on one or two workstations using an X window to show the charge status for 218 PCU's, the interface states, countdowns, system parameters, errors, and other information regarding the current state of the power conditioning. This display is maintained by a subprocess of the PCE and is independent of the GUI used for operator control of the PCE. The status display is illustrated in Fig. 65.31.

d. Timing system interface. Critical to the control of the power conditioning system is its interface to the OMEGA master timing system—the synchronization reference for the laser system. This system provides essential timing signals that are phase locked to the laser oscillator (an Antares™ cw mode-locked laser) whose 78-MHz master timing clock is the

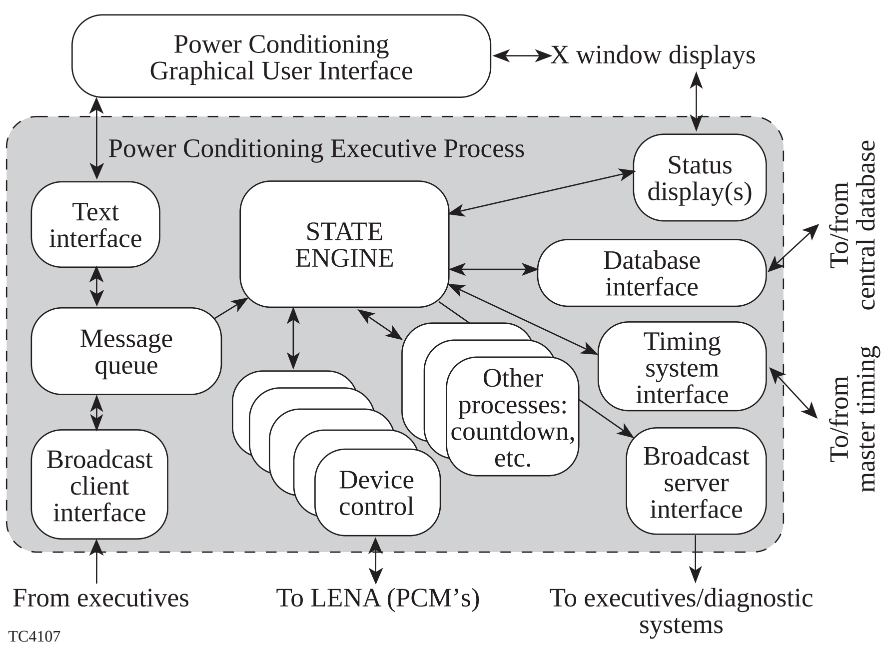

Figure 65.29
The Power Conditioning Executive Subprocesses exist within the executive computer and are composed of both *lightweight* and normal processes. For example, the Graphical User Interface (GUI) is a separate (normal) process, while the state engine and the message queue are examples of *lightweight* processes within the PCE process.

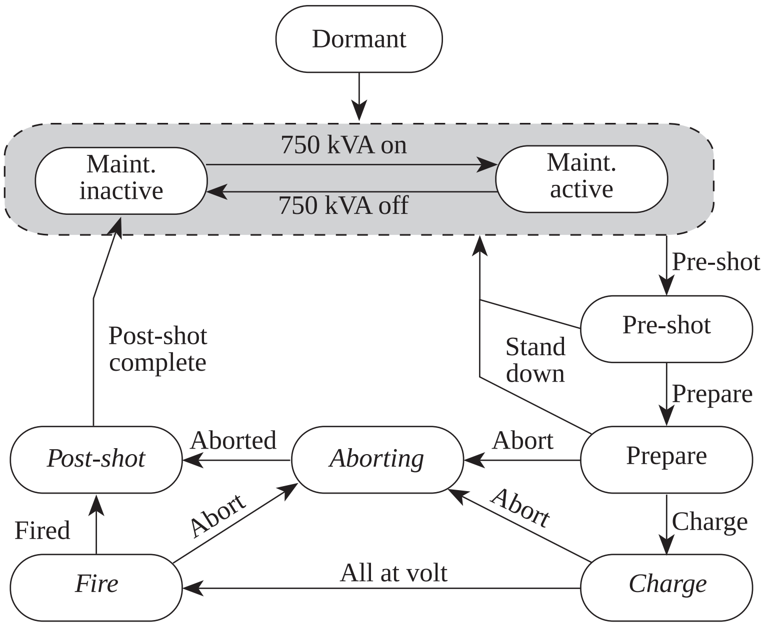

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Figure 65.30
The Power Conditioning Executive is fundamentally a *state engine* with several states and transitions related to the shot sequence of the laser system.

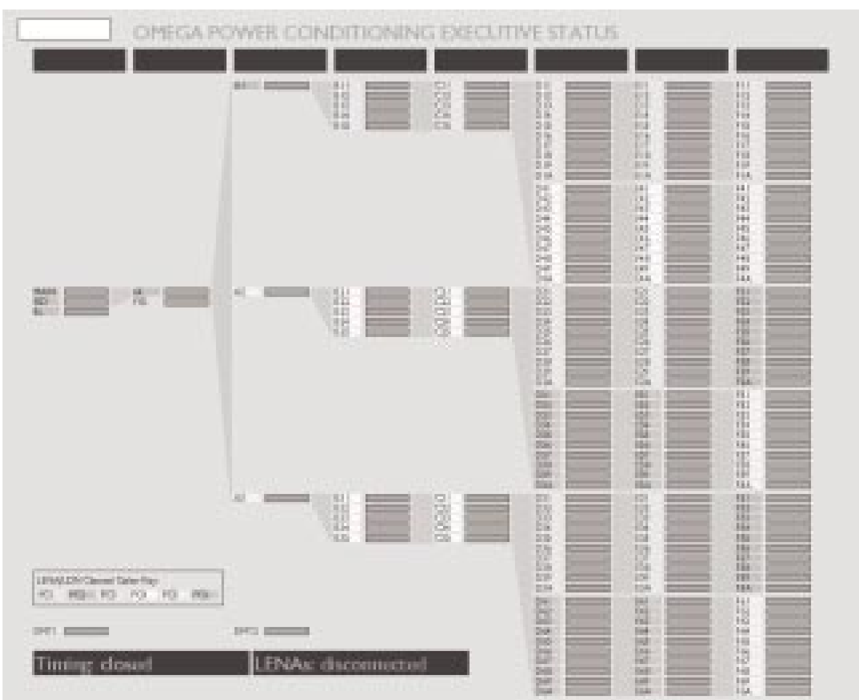

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Figure 65.31
The Power Conditioning Executive status display shows the operator the current status of each power conditioning unit (PCU), including its current voltage and error status during charge, as well as the countdown to the shot.

reference for the entire system. This allows all events that occur during the operation of the laser to be properly synchronized to the occurrence of the ~1-ns laser pulse. Without this precise synchronization, the laser system and its diagnostics could not operate.

The interface to the timing system allows the Power Conditioning Executive to synchronize itself to the timing system and to initiate and control the shot sequence. The timing system provides the PCE with a 0.1-Hz signal via the timing interface hardware illustrated in Fig. 65.32. To execute a laser shot, the PCE initiates and monitors the charging of the system capacitors. Once all capacitors are charged, the PCE waits for a 0.1-Hz signal and then enables the *T minus 10* event; this signals the preparation of many diagnostic subsystems for the shot. On the next 0.1-Hz signal (which is *T minus 10*), the PCE enables the *T equals 0* event—the actual shot, which will occur exactly 10 s later. Both the *T minus 10* and *T equals 0* events are referenced by electrical signals that are fiber optically coupled to numerous hardware devices, including the PCU's that initiate the firing of the amplifiers. These devices use the enable signals from the PCE to discriminate which of the 0.1-Hz pulses is the actual shot.

e. Database interface. The PCE is interfaced to an Ingres database that stores the post-shot data and maintains the various shot counters. A *Database Log Number* (*DBL#*) is incremented for all shots or aborts, and counters are used to keep track of the various shot types. The database keeps a precise record of the number of shots on each of the ~7000 flash lamps in the system, allowing for periodic maintenance in a timely manner. The post-shot data logged to the database can be used to review the amplifier performance on any shot, or to perform statistical analysis of amplifier performance over time. In addition, post-shot reports are generated from the database using this information, as well as other diagnostic data that are stored in the database after the shot.

An early version of the PCE used a separate process called the *Data Manager* to communicate with the database. This was necessary because of an incompatibility between the multithreaded PCE and the database API. Recent updates to the database system have allowed this functionality to be merged directly into the PCE, resulting in a significant improvement in performance as well as simplicity and reliability. The database API has been written in ANSI C for compatibility with a variety of other applications.

f. Broadcast. To support inter-executive communication (over Ethernet via TCP/IP), several libraries and subprocesses have been developed. One important implementation is the "broadcast" subprocess that allows any number of other executives or diagnostics to "listen" to messages from another executive, in this case the PCE. The PCE broadcasts state transitions, the shot countdown, and other shot-related information such as the type of shot and the database log number. In addition to these messages, the PCE transmits an empty message every few seconds as a "heartbeat" to allow other processes to verify that the PCE is still operating. This is performed to insure constant control of the high-voltage power-conditioning system.

g. LENA interface. Much of the lower-level functionality of the power conditioning subsystem is performed by the power conditioning units (PCU's), each of which contains a power conditioning module (PCM) that in turn contains a Neuron™[13] control device. These Neurons™ communicate via a proprietary network protocol called LONTalk™.[14] To communicate with the Neuron™ devices, the PCE and other executives make use of a process called the LON Ethernet network adaptor (LENA). This process was developed as part of the OMEGA Upgrade Project and can operate either on an IBM PC or SPARC workstation. As suggested by its name, the LENA acts as an interface between the proprietary network protocol of the Neurons™ and the Ethernet protocol (TCP/IP), which is used by the executives. (Six LENA's are used by the PCE to contact six distinct LONTalk networks among which the 218 PCM's are distributed.)

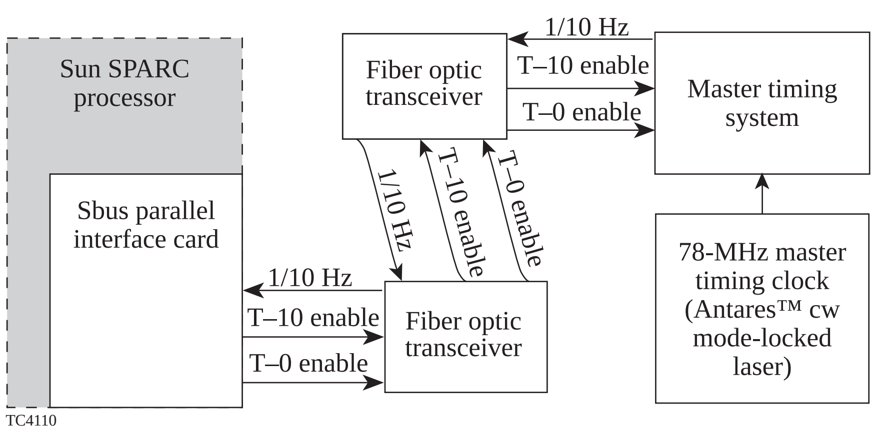

Figure 65.32
The interface to the timing system allows the Power Conditioning Executive to synchronize itself with the timing system and to initiate and control the shot sequence.

The LENA is composed of several parts, as illustrated in Fig. 65.33. The executive API (application programmer's interface) was developed in C++ and is directly accessed from the executive (PCE). It communicates, via TCP/IP sockets, with the LENA process, which may run on the same or another computer. The LENA process has a master loop that watches for either executive requests or asynchronous Neuron™ responses and relays these requests and responses to the appropriate destination. The LENA communicates with the LON via the manufacturer-supplied API, which was ported to Solaris at LLE for use on OMEGA. The LENA process was also developed using C++.

2. Power Conditioning Graphical User Interface (GUI)

One part of the message-queue system of the PCE is a command-line interface that is used mainly for development. In operation, the PCE is accessed via a Graphical User Interface. This GUI acts as a "front end" to the PCE, so that for operators, this is the only interface to the PCE. The GUI (illustrated in Fig. 65.34) has buttons for selecting state transitions as well as displays of the current database log number, the time, the elapsed time since the previous shot, the state of the enable lines, and the countdown. In addition, a scrolling window displays the text output from the PCE, and an option button allows the operator to select various procedures that are not part of the basic shot sequence.

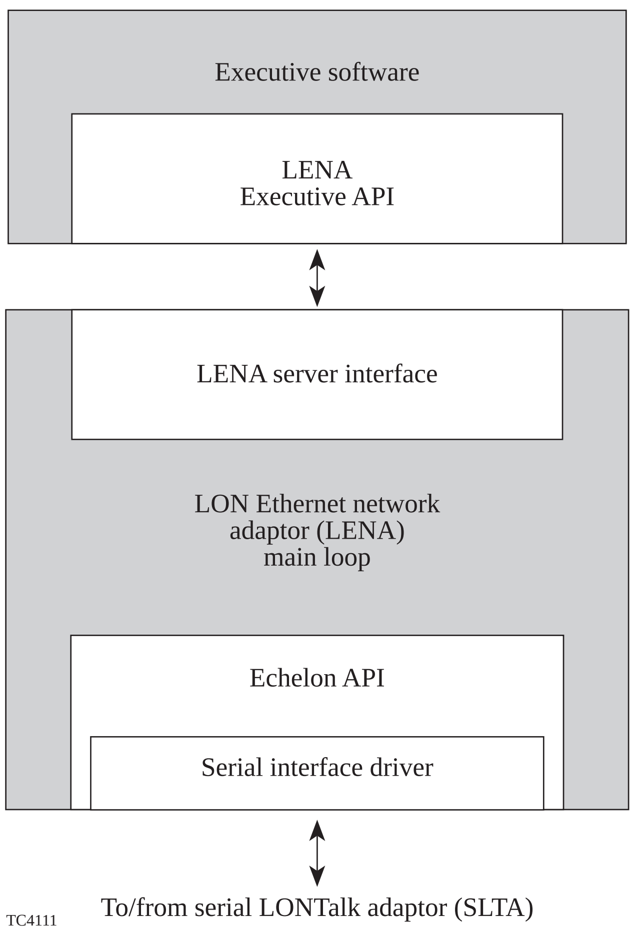

Figure 65.33
The LON Ethernet network adaptor (LENA) is a critical mid-level component in the control system, which connects the executives with the Neuron™ networks.

This Graphical User Interface was developed using the UIM/X Graphical User Interface Builder, which constructs the X/Motif user interface. Call-back procedures for the various buttons and windows were written in ANSI C.

The *look and feel* of this interface conforms with the standards established for the OMEGA executive processes. These standards were meant to create an aesthetic, functional, and uniform interface that will allow system operators to move comfortably to the various control executives, thus supporting a cross-training philosophy basic to OMEGA operations.

The Power Conditioning Executive workstation is equipped with two monitors so that both this GUI and the previously described status display are presented simultaneously to the operator.

3. Power Conditioning Unit (PCU)

As mentioned, each amplifier is equipped with a power conditioning unit (PCU) that is responsible for charging and discharging the capacitors for the execution of a shot. On a shot, the PCU first charges its associated capacitors to the requested voltage and then holds that voltage until the command is given to discharge into the flash lamps. The charge profile, holding parameters, various delay times, etc., are preprogrammed into the PCU and are constantly monitored during the shot sequence by the power conditioning module (PCM) and its Neuron™ processor. Deviations from expected performance are identified and acted on to insure safe, reliable operation of the system.

a. Power conditioning module (PCM). Each PCM contains one Neuron™ processor that is pre-programmed with the PCM firmware and is controlled by the PCE. The firmware performs all of the tasks outlined above and was written in a variation of the C programming language called Neuron C™. In addition to the normal C constructs, Neuron C includes several features for handling event-driven processes. These events are related to state changes in several hardware I/O lines

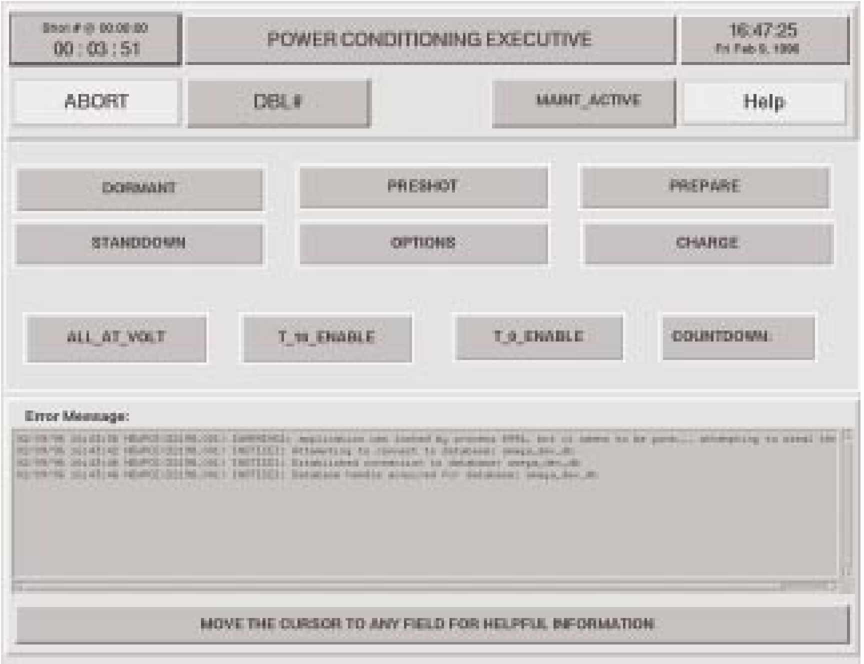

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Figure 65.34
The Power Conditioning Graphical User Interface provides access to the executive for the power conditioning operator. This screen illustrates many of the standard features of the OMEGA control system's GUI's, including a clock, time since last shot, and abort and help buttons.

and interfaces, or are related to the state of the so-called "network variables" that are used to communicate information between the Neurons™ and the executive.

4. Shot Sequence

All of the hardware and software systems described thus far have a single purpose—to fire the laser. A laser shot is a carefully orchestrated sequence through system states that charges and discharges the PCU's, then propagates a laser pulse. It requires precise and flawless operation of 218 amplifiers. The entire sequence takes about 5 min and is repeated every 30 to 60 min. A variety of shot types are possible, but all shots (assuming there is no abort) follow the sequence illustrated in Fig. 65.35.

The normal intershot state is called "maintenance."[15] It can be either "maintenance active," meaning that the 750-kVA power supply is turned on, or "maintenance inactive," meaning that the supply is off. The 750-kVA power is controlled by the facility interlock executive (FIE), which provides most of the top-level safety interlock control functions. The PCE uses the broadcast system to communicate with the FIE to determine the state of the 750-kVA power. The PCE can request 750-kVA power be turned on but cannot progress to the shot sequence until the FIE has turned on the 750 kVA.

a. Pre-shot. The shot sequence begins with the pre-shot state during which the "shot template" is loaded. This template contains a list of the amplifiers to be used and all of their relevant shot parameters, including charge voltages, various thresholds, and the required trigger delays.[16] This information is displayed in the scrolling window on the GUI and is also available for individual amplifiers on the status display. Selected amplifiers on the status display show black; nonselected amplifiers are blue.

At this stage, if the operator or shot director notices some problem with the shot, it is possible to terminate the shot sequence without an abort. No data is logged to the database, and the database log number is not incremented in such an event. Once the template is accepted by the operator and shot director, the sequence proceeds to the "prepare" state by pressing the "prepare" button on the GUI.

b. Prepare. In the prepare state, system configuration information (from the template) is downloaded to the Neuron™ modules (PCM's) via the LENA's. At completion of the download, the status of each amplifier on the status display will turn from black to green and then to white, indicating to the operator that the selected amplifiers are ready to charge. In this state, it is still possible to terminate the shot sequence without an abort.

Dormant ↓	PCE is not running.
Maintenance ↓	PCE is running; “heart beat” being broadcast, toggles between active and inactive based on communication with Facility Interlock Executive.
Pre-shot ↓	Template is read; sanity checking; template is reviewed by operator and shot director using Graphical User Interface (GUI).
Prepare ↓	Communication with PCM’s and timing interface is established, database log number is obtained; template is downloaded to PCM’s; status of amplifiers is displayed.
Charge ↓	PCU’s begin charging. Voltages are polled and displayed, charging can take from a few seconds to several minutes, depending on the voltages; automatic transition to fire when all amplifiers are at voltage.
Fire ↓	PCU’s are “armed” to fire; timing interface is controlled to initiate shot.
Post-shot ↓	Post-shot data is read from PCM’s; data is logged to database.
Maintenance	PCE returns to maintenance mode.

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Figure 65.35
A typical OMEGA shot sequence carries the system from its dormant or maintenance state through pre-shot, prepare, charge, fire, and post-shot, and returns it to the maintenance state. In each state, various conditions must be met, and tasks performed, before proceeding to the next state. Note that this is a *typical* shot sequence. Many other transitions are possible, particularly in an **abort** condition, as illustrated in Fig. 65.30.

c. Charge. When all selected amplifiers show “ready,” it is then possible to progress to the “charge” state. The operator selects “charge” from the GUI, and the amplifiers begin to charge after waiting the requested individual charge-delay times. This is the last transition in the shot sequence that is operator initiated (aside from an abort). While the capacitors charge, the PCE polls the voltages and displays a yellow bar on the status display. Minimum and maximum voltages for each amplifier stage are also displayed. When an amplifier reports “at voltage,” the display bar turns green, and when all amplifiers are fully charged, the PCE automatically proceeds to the “fire” state.

d. Fire. In the “fire” state, the shot-timing sequence described previously is initiated, and a countdown is displayed on both displays. This countdown is also broadcast to any processes that may require this synchronization.

e. Post-shot. After the shot, the PCE automatically proceeds to the “post-shot” state, during which the PCM’s are polled for a variety of recorded information to be logged to the database. In addition, the shot type, shot time, and other shot-related data are logged. Once data logging is complete, the PCE returns automatically to the “maintenance” state and is ready for the next shot sequence to be initiated.

5. Error Handling

In addition to the normal sequencing of the PCE, a large portion of the system is dedicated to proper handling of error conditions. Great care has been taken to ensure that the PCE will remain operational and function properly in the event of a wide variety of possible error conditions.

a. Abort. The PCE is designed to accept and respond immediately to any abort messages resulting from an unrecoverable error condition detected during the shot sequence. These may come from the user interface, another executive, or one of the subprocesses within the PCE itself. The PCE responds to an abort by first disabling the timing interface, thus preventing the shot from occurring. Next, the PCE sends an abort message to each active PCM, ceasing the charging process and dumping the charge through the emergency dump resistors. Once the system is aborted, the PCE automatically proceeds to the “post-shot” state and records much the same information that is recorded on a normal shot.

b. Casualty mode. One field in the template that is loaded at pre-shot is a “casualty mode” flag for each amplifier. If this flag is on, it indicates that a detected error on this amplifier is not to be treated as an abort condition. In this mode, the amplifier is flagged as inactive and the status display will show red, but the shot sequence will proceed for the remaining amplifiers. This mode was added during the activation of the laser system to allow amplifiers with noncritical defects to be operated.

Future Directions

Although the PCE is used effectively for routine operation of OMEGA, many aspects of the system could be improved. Several of these areas are outlined in this section.

1. LON Throughput

Currently, the LON throughput is severely limited by various aspects of the hardware and software. This affects the ability to read certain diagnostic information from the power conditioning modules and the receipt of notifications that occur during critical shot-related events. Work is ongoing to improve this throughput at several levels.

2. Templates

On each shot, the PCE is now configured by using a so-called *flat file* that contains the voltage and timing parameters for each amplifier. Ultimately, this information will be contained in an overall *System Template*, a comprehensive description of the entire laser system configuration for each intended shot. It will be created and stored hierarchically in the Ingres database system and will include an automatic validation scheme. Much work in the coming months will be dedicated to the creation and deployment of this template system for all of the OMEGA control systems.

In addition to the power conditioning parameters, a complete description of the shot will eventually be logged at shot time. In the present implementation, much of this information is either not available to the computer or not directly available to the PCE for logging. As the templates are developed, this information will become available and will be logged at shot time. The goal is to create an electronic database that contains all pertinent information about a shot.

3. Graphical User Interfaces

Both the operator interface and the status display for the system have features that have yet to be implemented. These programs were developed using different tools and techniques and are driven from different processes within the executive. The appearance and operation of the system can be improved by merging the two into a single process and standardizing their *look and feel* using the same technique to implement them.

Conclusion

The power conditioning subsystem is central to the operation of the OMEGA laser system. The Power Conditioning Executive (PCE) and Power Conditioning Graphical User Interface (PCEGUI) are key software components that control this subsystem. Together they provide the operator interface, state engine, interprocess communication, and device control, which are essential to the operation of the laser system. The primary task of this subsystem is to perform a *shot sequence*, which entails not only the charging and firing of the laser amplifiers but also careful monitoring of the entire laser system to ensure safe and controlled operation. It is also responsible for logging shot data for later analysis.

Implemented in C/C++ and making use of X/Motif and threads, these programs take best advantage of the state-of-the-art software tools to provide an efficient and effective interface to the power conditioning hardware. Graphical User Interfaces (GUI's) make the system easy to operate and present the status of the system in an attractive and accessible format.

To perform its task, the PCE interacts continuously with a central database system, a master timing interface, other executives, and the Neuron™-based power conditioning modules (PCM's). Judicial use of *threads* (or *lightweight processes*) and interprocess communication allows these many tasks to be performed in concert with one another.

The successful deployment of this subsystem, as part of the entire OMEGA Upgrade Project, has been the work of many individuals over several years. Many more years of work remain to implement all of the desired aspects of this new OMEGA laser control system.

ACKNOWLEDGMENT

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REFERENCES

1. During its activation, the OMEGA laser achieved 40-kJ UV energy on target, matching the previous record obtained on the Nova laser at Lawrence Livermore National Laboratory.

2. TCP/IP (Transmission Control Protocol/Internet Protocol) is the prevailing standard for network communication over the Internet.

3. Definition Document: Upgrade Control System: S-AA-G-01. Laboratory for Laser Energetics, University of Rochester, September 1993.

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5. Definition Document: OMEGA Upgrade Hardware Timing System: B-BU-R-02. Laboratory for Laser Energetics, University of Rochester (unreleased).

6. Specification—Power Conditioning Controls for the Rod and Disk Amplifiers of the OMEGA Upgrade: C-PC-G-01, Rev. B, Laboratory for Laser Energetics, University of Rochester, May 1992.

7. Computer Program Design Document—PCU Control Module: C-PC-F-01, Rev. A, Laboratory for Laser Energetics, University of Rochester.

8. Many of these subprocesses are threads, also known as lightweight processes. These threads are tightly coupled but asynchronously executing processes within a single program and are implemented using Sun's multithreaded Solaris operating system API.

9. B. Stroustrup, *The C++ Programming Language*, 2nd ed. (Addison Wesley, Reading, MA, 1991).

10. B. W. Kernighan and D. M. Richie, *The C Programming Language*, 2nd ed. (Prentice Hall, Englewood Cliffs, NJ, 1988).

11. Transient states are shown in italics in Fig. 65.30.

12. Previously, the database log number was known as the shot number. It is incremented on each shot or aborted shot, including "software" shots, and is used to uniquely identify information stored in the database. Other counters are also incremented depending on the type of shot.

13. The Neuron™ name is a trademark for single-chip network-based microcontrollers produced by Echelon Corporation.

14. LON stands for local operating network.

15. Note that the "dormant" state means that the PCE is not operating.

16. Each PCU fires on a pre-programmed delay relative to the T–0 trigger. In addition, each amplifier has a charge delay to allow all amplifiers to reach voltage at approximately the same time.