Overview of the Design and Implementation of the OMEGA Laser Control System Software

Over the last four to five years, the Laboratory for Laser Energetics has been in the midst of an Upgrade Project, which has resulted in the new OMEGA inertial confinement fusion (ICF) laser system. The previous OMEGA consisted of a 24-beam laser with its associated controls and diagnostics. Many of the components of the previous system were manually adjusted, and the control system consisted of several Digital Equipment Corporation VAX and PDP-11 computers and a custom-designed power conditioning computer system. Several IBM/PC–based diagnostics were also a part of this system. Much of the original control software had been written in the Forth language, but over the years it was largely rewritten in Fortran and C, making extensive use of DEC-specific libraries and language extensions.

In addition to upgrading the hardware for the new 60-beam laser, all of the laser controls were also redesigned. This redesign was necessary for a variety of reasons, the most compelling of which was the motorization of virtually every movable optic and component in the system. Other factors included the desire for more modern user interfaces and more platform-independent software systems (to take advantage of the inevitable evolution in computer hardware and operating environments). The success in achieving these goals will be reviewed in a later section. First, an overview of the current design and some implementation details will be presented.

Laser Control System Overview

As shown in Fig. 67.25, which also appears in Ref. 1, p. 34, the top-down design of the newly upgraded OMEGA laser control system consists of an interconnected network of software executives. This control system has been developed using state-of-the-art techniques and tools, included C/C++, X-based Graphical User Interfaces (GUI's), Inter-Process Communication (IPC), and Lightweight Processes (LWP's or threads).

1. Choice of Platform

In choosing the primary computer platform, the factors that were considered included hardware and software price, speed, packaging, support and availability of operating systems, programming languages, and configuration management tools.

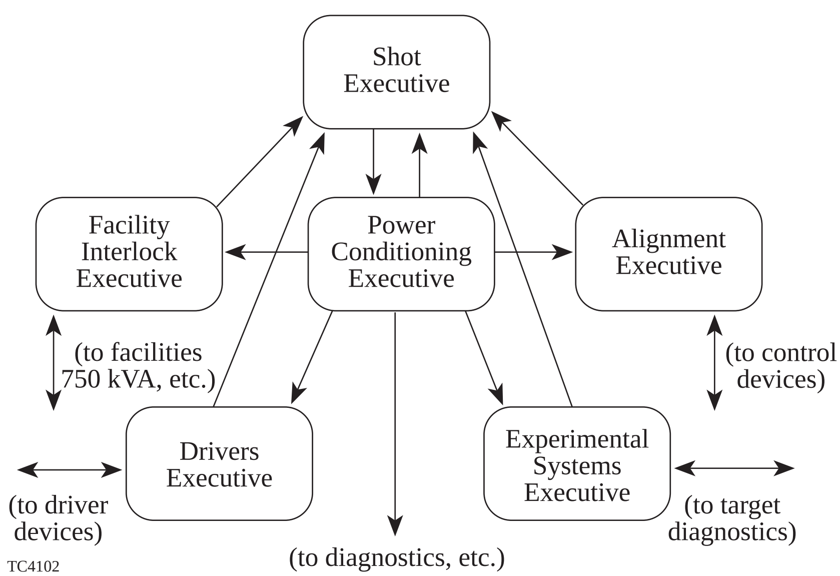

Figure 67.25
The laser control system is distributed over several *Executives* that are interconnected via Ethernet using TCP/IP. Each Executive performs or oversees one aspect of the laser operation and interacts with its associated devices.

a. Computer hardware. The choice of platform for the primary control computers was a difficult one, and several of the recently developed *Reduced Instruction Set Computers (RISC)* were considered before the Sun Microsystems' SPARC architecture was selected. Other platforms that were considered included the DEC Alpha, IBM RS-6000, and HP 735. As mentioned, the primary factors used in selecting the computer hardware were price, speed, packaging, and support. Another consideration was the installed base at LLE and availability of experienced support people within the Laboratory. In the end, since there was no clear winner in the technical areas, this latter consideration may have been the deciding factor since LLE already had a large, installed base of Sun Microsystems' equipment and several years of experience with the administration of Sun systems.

b. Operating system. The operating system was a key factor in the choice of platform for this project (see previous paragraph). During the design phase of the control system it was decided that available standards would be followed wherever possible to ensure the longevity of the control system. For operating systems, it was decided that conformance to the ANSI/ISO/IEEE POSIX (**P**ortable **O**perating **S**ystem **I**nterface for Uni**X**) standard would be the selection criterion. Although the POSIX standard is designed to be generally applicable, this virtually implied that a UNIX operating system would be used. Although all of the platforms considered had available operating systems that claimed some level of POSIX conformance, some platforms were dropped from consideration because of an apparent limited support for their POSIX-conforming operating environments. The OMEGA executive-level computers are currently running Sun's Solaris 2.5 operating system, which complies with the POSIX.1[2] and POSIX.2[3] standards for operating system interfaces.

c. Programming languages. The primary languages used for this project were ANSI standard C[4] and C++,[5] based on standardization and performance. It was also decided that ANSI Fortran could be used where applicable. As the project has evolved, portions of the system have also been implemented using the PV-WAVE[6] system.

d. Threads. *Threads,* also known as *lightweight processes,* were identified in the design phase of the system as an important and valuable tool for implementing the control system. These threads are tightly coupled but asynchronously executing processes within a single program and are implemented in the OMEGA control system using Sun's multithreaded Solaris operating system API.

e. Graphical User Interfaces builders. As will be seen later, a key element of the OMEGA control system is the design of the various Graphical User Interfaces (GUI's). Two GUI builders[7] were employed in the development of the OMEGA control system: the UIM/X system from Visual Edge Software and the Data Views from V. I. Corporation. Each has advantages and disadvantages that make them both valuable. These GUI builders generate code for X/Motif GUI's, which is in turn linked with the application software through locally developed libraries and so-called "call-backs."

f. Configuration management tools. As mentioned, the new OMEGA control system is intended to be easier to maintain and more durable than the previous system. A key factor in the longevity of any system, including software systems, is configuration management. The OMEGA system employs the well-established UNIX/POSIX configuration management tool called **make,** and all revisions to source code are maintained by SCCS (Source Code Control System).

g. Auxiliary computer systems. A number of auxiliary systems on OMEGA are not operating on the Primary computer platform. The vast majority of these are IBM/PC-compatible systems, which are used generally for reasons of convenience or hardware interface availability. Wherever possible, the same languages and tools were used for developing software on these auxiliary systems, several of which will be mentioned in later sections.

The Executives

The upper-level control software for OMEGA is divided into several major programs, which are called *executives,* as shown in Fig. 67.25. These executives vary in complexity and function; however, they all share a number of features and make use of a number of the same subprocesses to perform their various tasks. Each executive follows, in some way, the vertical layout illustrated in Fig. 67.26. For the laser system to operate, several, if not all, of these executives must be operating and communicating with their associated devices and with each other. The next few sections will describe the design of several of the executives currently in use or being implemented; later sections will discuss the interface and support systems that are common across the executives.

1. Shot Executive

Although it was not available during the activation of the laser system, a key element in the ultimate operation of the laser system is the Shot Executive, also known as the Shot Supervisor. This executive is under the direct control of the

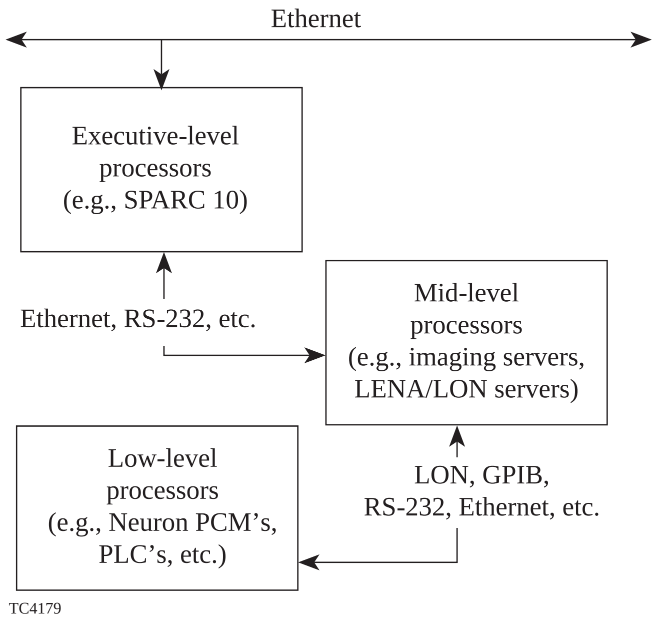

Figure 67.26
The laser control subsystems are distributed vertically into executive, mid-level, and low-level processors. This organization facilitates both modular code development and reusability.

Shot Director, who is the single individual responsible for the operation of the laser.

This executive serves several purposes. In its current form, it acts primarily as a sort of *clearing house* for status information from various other executives and processes. It monitors the state of the laser system and determines whether the various subsystems are ready to proceed to a new state, as requested by the Power Conditioning Executive (PCE). This allows the Shot Director to monitor the system and, in the event of some problem, make the decision whether or not to proceed into the next state. This process of moving from state to state will be discussed in more detail in a later section and was discussed in much greater detail in Ref. 1, pp. 34–43.

This executive makes use of a library of C++ classes and functions that implement a state engine and messaging system. This library was generalized from code developed for the Power Conditioning Executive, which was discussed in detail in Ref. 1 and is also used by the Experimental Executive (discussed later in this article).

In addition, the Shot Executive uses the *Broadcast* system (described in Ref. 1, p. 38) to communicate with the other executives. A standardized Graphical User Interface (GUI) allows the Shot Director to abort the *shot sequence* and to intervene should any other executive indicate that it is not prepared for a requested system state transition (see subheading Standard Graphical User Interface later in this article).

2. Facility Interlock Executive

The Facility Interlock Executive (FIE) was the first executive to be operational in the OMEGA control room. It provides a user interface to access all doors, shutters, personnel monitors, signs, beacons, sirens, and power cutoffs that constitute the safety-related subsystems of the OMEGA laser. In addition, the FIE communicates via the *Broadcast* system to the Power Conditioning Executive to inform it of the state of the 750-KVA power that operates the OMEGA power conditioning subsystem.

The FIE is implemented in two parts: The executive part is a standard GUI, which acts as both operator interface and status display. This part communicates over Ethernet using a low-level protocol to a Programmable Logic Controller (PLC), located in the main laser relay panel. This PLC has the safety-related logic programmed into it to ensure safe operation of the facility, even if the PLC should lose contact with the executive process. The PLC subsystems of OMEGA are discussed in more detail later.

Because of conflicts with the API (Application Programmers Interface) for the PLC, the FIE could not be implemented with the *threads* that were used in most of the other executives. This resulted in a number of changes in its design and increased the difficulty of its implementation.

3. Power Conditioning Subsystem

The design and implementation of the power conditioning subsystem has been described in detail in Ref. 1, pp. 34–42.

4. Alignment Executive

One of the most critical subsystems for activation and continued operation of the laser system is the Alignment Executive (AE). This executive provides access for the alignment operators to the several thousand controllable devices throughout the laser system. These devices are controlled individually or in groups by specially designed Neuron™[8] control modules, including the Two-State Control Module (TSCM), Single-Axis Control Module (SACM), and Dual-Axis Control Module (DACM). These devices are accessed via the LENA interface (see Ref. 1, pp. 38–39).

The AE itself has gone through several evolutionary stages, from an early form based on the Drivers Executive (see next paragraph), to its current, highly graphical interface. In its current form, the GUI, which was developed using the DataViews GUI builder, has interactive graphical representations of the various control devices, which allow both control and status displays. Additional pull-down menus allow more detailed control, as well as execution of macro scripts and saving and restoring of device locations.

5. Drivers Executive

Although recently largely rewritten for use in the Control Room, the Drivers Executive was the first executive made operational on the OMEGA system. In many ways, the Drivers Executive contains all of the features of the entire laser control system: device control, energy diagnostics, access to imaging, and GUI's. This made its implementation and deployment in the early stages of the OMEGA Upgrade extremely difficult. To make the job easier, the task was divided between several developers, and the executive divided into several semi-autonomous subprocesses (illustrated in Fig. 67.27).

While many aspects of this early executive have been eliminated or redesigned, the process of developing it was key to the evolution of the current design. In the current design, for example, the *process interface* has evolved into the current, much simpler *Broadcast* system or been replaced by direct interfaces.

Most of the diagnostic subprocesses of the Drivers Executive are still in place, including the imaging subsystem (see next paragraph plus later subsection on imaging).

6. Laser Diagnostics

Laser Diagnostics is not a separate executive *per se* but is a complex set of processes run in cooperation with the executives to obtain diagnostic information about several aspects of the laser system.

Associated with the Drivers Executive is a sophisticated suite of acquisition processes that interact with CAMAC-based diagnostics and oscilloscopes via several GPIB (General Purpose Interface Bus) interfaces.

Other key diagnostic interfaces are those for the calorimeters, which are Neuron™-based devices, and the harmonic energy diagnostic (HED) (see later subsection on imaging).

7. Experimental Systems Executive

The Experimental Systems Executive (ESE) is currently still in the design phase. In its first form, it will be similar in

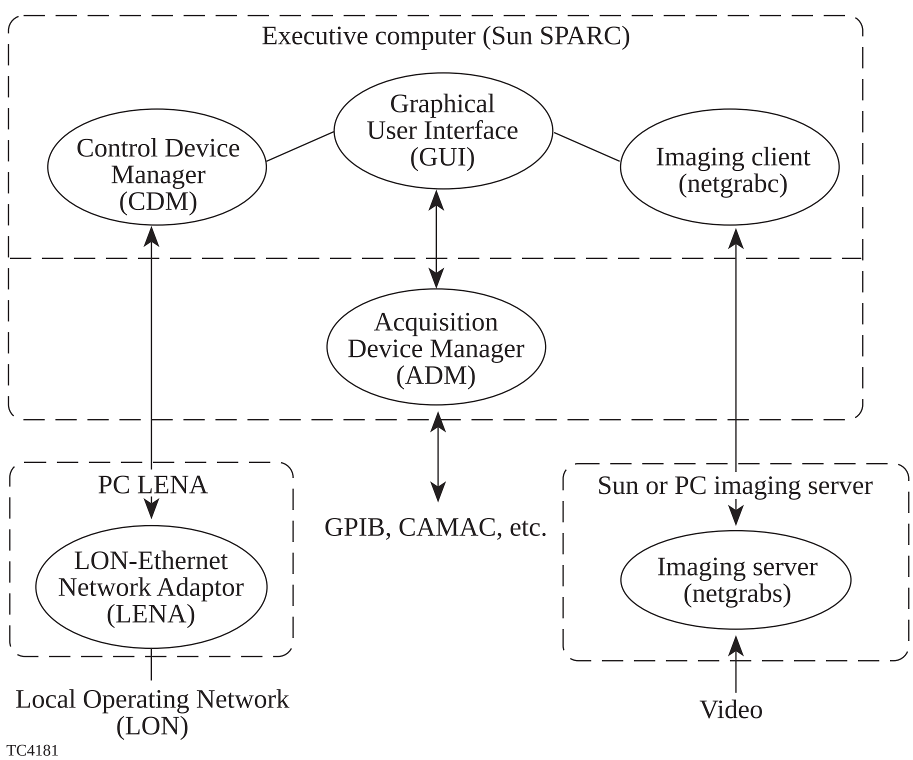

Figure 67.27
The original Drivers Executive included several important design features, i.e., distributed processing and a Graphical User Interface (GUI).

function to the Shot Executive (SE). It will coordinate the status information from the numerous experimental diagnostic subsystems and interact with the SE to allow the shot sequence to proceed.

a. TVS/TPS—Target Viewing and Positioning System. One subsystem of the ESE has been in operation for some time—the target viewing and positioning subsystem. This GUI provides access to the imaging system used for target viewing, and to the PLC used for control of the TVS controls and target positioner.

Interface/Support Systems

1. Imaging

The first operational system within the Alignment Executive on the upgraded OMEGA laser was the electronic imaging subsystem, which is used for alignment. This system includes nearly 100 cameras, video multiplexors, frame grabbers, and a cable TV–style video distribution system.

The control software for the imaging subsystem is divided into several layers, as illustrated in Fig. 67.28. Although a number of different GUI's have been and are being used, the same basic *netgrabc/netgrabs* subsystem is used in several OMEGA subsystems including the Alignment Sensor Packages (ASP's), Harmonic Energy Diagnostics (HED's), Target Viewing System (TVS), and Imaging X-Ray Streak Camera (IXSC).

In addition to being able to select, view, save, and restore images from the numerous cameras throughout the laser system, the imaging system incorporates an extensive suite of image-processing routines that provide the alignment operators with immediate feedback on the positioning of the laser beams. This includes overlay of reference locations from the database (see 2. Database Interface) and computation of centers using various algorithms.

a. Alignment Imaging Graphical User Interface. A specialized and highly sophisticated GUI was developed to operate of the alignment imaging subsystem. This interface continues to operate in conjunction with the Alignment Executive.

2. Database Interface

The executives are interfaced to an Ingres database, which stores the laser and experimental data and maintains the various shot counters, including the *Database Log Number (DBL#)* that is incremented for all shots or aborts, and counters for the different shot types. As an example of the database's function, a precise record of the number of shots on each of the system's many thousand flash lamps is maintained. These records allow periodic maintenance to be performed 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 earlier version of the executive software used a separate process called the *Data Manager* to communicate with the database. This was done because of an incompatibility be-

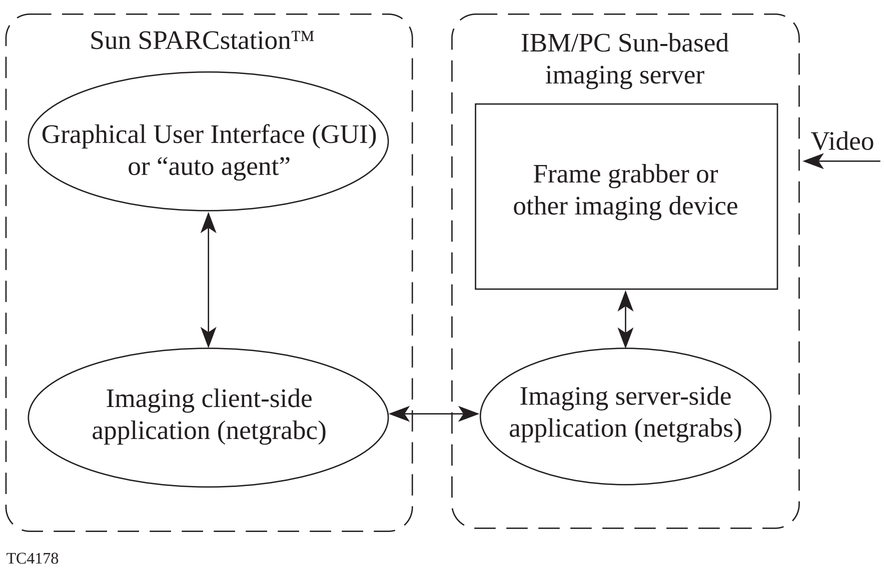

Figure 67.28
The imaging system design is general purpose and based on a network imaging server. This server is accessed over Ethernet via TCP/IP using Remote Procedure Calls (RPC's), and employs a Graphical User Interface (GUI).

tween the multithreaded executives and the database API. Recent updates to the database system have allowed this functionality to be merged directly into the executives, 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 applications.

a. Image/data archive. One lesson learned on the previous OMEGA laser system was that there is a need for a coordinated system to deal with experimental data, including images from film and electronic detectors, as well as trace and point data from various detectors.

The approach taken on the new OMEGA system is to provide an interface through the Ingres database to a separate archive of this data. Currently, there is an experimental interface to this archive making use of a World Wide Web interface system (e.g., Netscape) to allow access to the data from any of the various computer systems within the Laboratory. The design of the image/data archive is illustrated in Fig. 67.29.

3. Standardized Graphical User Interface

Most of the executives have been designed with a standardized Graphical User Interface (GUI), both to maintain a uniform and aesthetic appearance and to aid the operators in quickly obtaining the basic information and controls needed for efficient operation of the laser system. The visible features of the standard GUI can be seen in the Power Conditioning Executive GUI shown in Fig. 65.34 of Ref. 1.

The lower section of the screen features an infinitely scrollable (but clearable) window in which various operator messages are displayed. These messages are also logged to a file, for so-called *postmortem analysis*, should some error occur during operation of the laser system.

The upper portion of the screen features several standard displays and controls, including the clock time, time since last shot, database log number, executive title, and an abort button. These displays and controls are standard across the executives.

The center portion of the screen is used uniquely by each executive for its unique controls.

4. Broadcast

The broadcast interface is described in Ref. 1, p. 38.

5. LENA Interface

The LENA interface is described in Ref. 1, p. 38.

6. PLC's: Programmable Logic Controllers

Several of the subsystems use Programmable Logic Controllers (PLC's) as part of their construction. Several types are being used in the OMEGA system. Of these, two particular

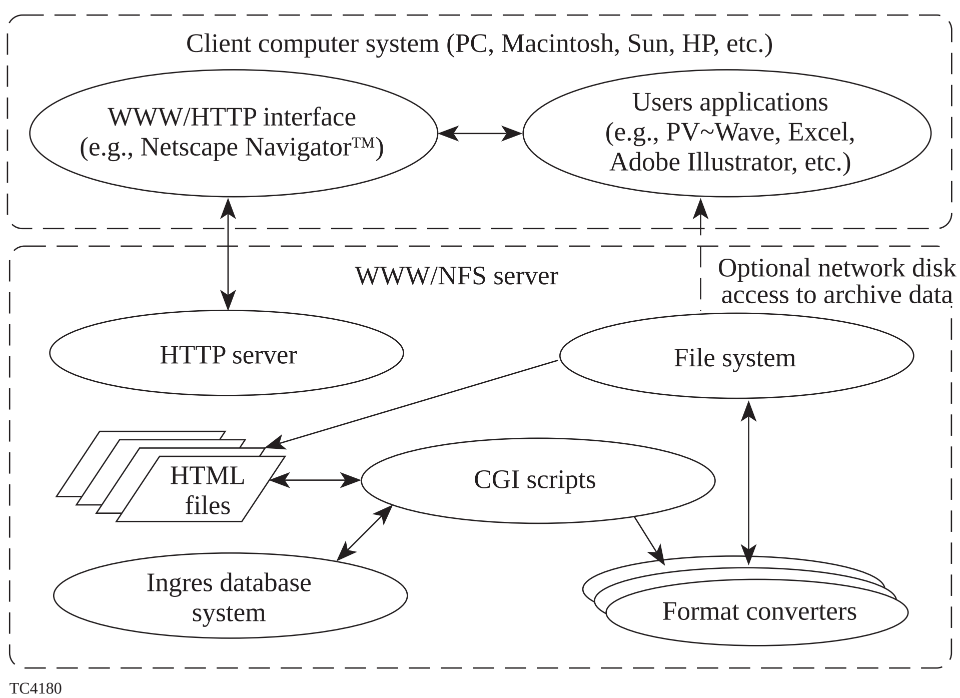

Figure 67.29
The LLE Image/Data archive is designed for easy access from throughout the Laboratory via World Wide Web interfaces such as Netscape Navigator™.

PLC systems will be discussed: one produced by Square D, and another by GE Fanuc.

The Square D systems are being used in facility interlock and for control of the periscope mirror assembly (PMA), which is part of the ultraviolet (UV) alignment system and controlled through the Alignment Executive.

The GE Fanuc systems are used for main target vacuum and other target area controls (via the so-called HexPent[9] controllers), including the auxiliary vacuum systems, target positioner, and ten-inch manipulator (TIM) controls, as well as various target-area diagnostic system controls.

Generally, PLC's have been chosen in areas where inexpensive but highly reliable systems were desired for either local manual or automatic control of some subsystem.

Future Directions

Although the OMEGA laser system is now in operation and proceeding with its planned experiments, many aspects of the control system (several of which are outlined below) still remain to be developed or extended.

1. Automatic Alignment

The current system provides tools for alignment personnel to view the position of the laser beams, as well as control this position by adjusting the associated mirrors and other devices. In spite of this, given the large number of beams and even larger number of movable devices, it is unrealistic to expect humans to align the entire laser system within the 1-h shot cycle for which the system was designed. As a result, an automatic alignment system was envisioned where the measured beam positions would be folded back to produce computed moves so that the laser could be automatically aligned under software control.

Presently the position of the beams is measured and the mirrors are computer controlled, but closing this loop involves a substantial task of developing algorithms for computing the mapping of the beams' position to motor movement, as well as dealing with errors that can occur during the alignment process.

2. Templates

An important concept in the early design of the laser control system was the implementation of *templates*. These templates will provide predefined configurations for the laser and for both laser and experimental diagnostics for each shot. A hierarchical scheme is envisioned for storing, merging, and verifying laser-device configuration, power-conditioning configuration, diagnostic configuration, and target chamber configuration, as well as recording this configuration after the shot.

At present, only limited portions of this system have been implemented, but as the system continues to evolve, we continue to move its design closer to this design goal.

3. On-Line Help

No system is complete without documentation. For the OMEGA laser, it is intended that most if not all of the documentation for the system will be available as on-line help, so that system operators will always have, at their fingertips, the facility to locate the information they need to answer any question about system operation.

To date, unfortunately, time and resources have not permitted the inclusion of this on-line help facility. When it is implemented, the current plan is to make use of the same World Wide Web interfaces that are being used for access to the image/data archive system. Some preliminary work along these lines has already begun.

4. Target Diagnostic Systems

Although they are not strictly part of the laser control system, a number of the target-area diagnostic systems are equally critical to safe and efficient operation of the laser as an experimental facility. As such, software for these systems is given equal priority and is currently under development.

5. Evolution

A goal of the upgrade of the OMEGA control system is a system that can grow and evolve with time. This goal was kept well in sight for this implementation, but much could be improved to prepare for the inevitable changes to come in computer systems and associated technology. As an example, as the POSIX.4 standard for lightweight processes becomes official and is supported, it would be prudent to convert the existing lightweight processes to this standard. Additional modularization and documentation of hardware-dependent subsystems would also be beneficial.

Summary

The control software for the OMEGA laser is composed of several major executives and supporting subsystems. Good design practices, including the use of both centralized and distributed control concepts, help keep the system manageable.

A set of semi-autonomous processes called Executives perform the major control functions, with the help of several interface and support programs.

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

To perform their tasks, the various Executives interact continuously with a central database system, a master timing interface, other Executives, the Neuron™-based control modules, and various other devices. 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 control system, 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 desired aspects of this new OMEGA laser control system.

ACKNOWLEDGMENT

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6. PV-WAVE™ is a registered trademark of Precision Visuals, Inc. It is an interactive environment for data analysis and plotting.
7. A GUI builder is a tool and environment for interactive construction of GUI's.
8. The Neuron™ name is a trademark for single-chip, network-based microcontrollers produced by Echelon Corporation.
9. The HexPent controllers are so-named because of the hexagon and pentagon formation of each functional section of the target chamber support structure.