scribed, we have been able to take advantage of Common Lisp's powerful programming environment to realize efficient, real-time applications. (See [5] for a discussion of "soft real-time" applications for which G2 is particularly well suited and of a Space Shuttle monitoring application. Also see Rocky Stewart's sidebar in this issue describing an application at Biosphere II.)

Use of these techniques on standard hardware platforms has only become practical in recent years, as sophisticated implementations of Common Lisp have become commercially available on those platforms. By strictly controlling the styles of programming used within the language, we have been able to use Common Lisp as a practical language for large real-time application development and delivery.

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Biosphere 2 Nerve System

Rocky L. Stewart

Biosphere 2 (Earth being Biosphere 1) is an experiment in closed system ecology. It is a steel and glass structure about the size of three football fields and has a volume of more than three million cubic feet. The purpose of the project is to demonstrate the viability of materially closed ecosystems—a sort of bioregenerative life support system—where water, air, and food are recycled. Later this year, eight people, called *Biospherians,* will be sealed inside Biosphere 2 for two years with only power and information being exchanged with the outside. A major part of this project is an expert system-based environmental control and monitoring system called the "Nerve System."

The ecosystems of Biosphere 2 are varied and complex. There are seven distinct biomes including a 30-foot-deep ocean, complete with waves, tides, and a coral reef including a rain forest with a 50-ft. mountain, waterfalls, and clouds. There is also a desert, marshland, savannah, an intensive agricultural biome where most of the food will be grown, and a habitat where the Biospherians will live during the experiment. Several thousand species of plants, animals, and insects will live in these biomes.

Due to the complexity of these ecosystems, a sophisticated and reliable control and monitoring system is required to ensure the success and safety of both the ecosystems and the Biospherians. To fulfill this requirement, a Nerve System consisting of a broad-band network, several HP9000 work stations, and a control and monitoring hierarchy of expert systems was developed using G2, a Lisp-based, real-time, object-oriented expert system development environment from Gensym Corporation.

After several available traditional control systems were reviewed, G2 was chosen for the project because of its ease of use and its high degree of integration between rules, objects, and graphical displays. Also, G2 rules are interruptible, thus allowing the developer to control data acquisition and response times. Controlling the heating, ventilation and air-conditioning (HVAC) systems of Biosphere 2 is a typical real-time control problem. In the past, Lisp would not have been considered a candidate to solve this problem due to response time limitations imposed by garbage collection. G2, however, is carefully designed to eliminate the garbage collection of Lisp, thus reducing the chance of a delayed reaction at a critical moment.

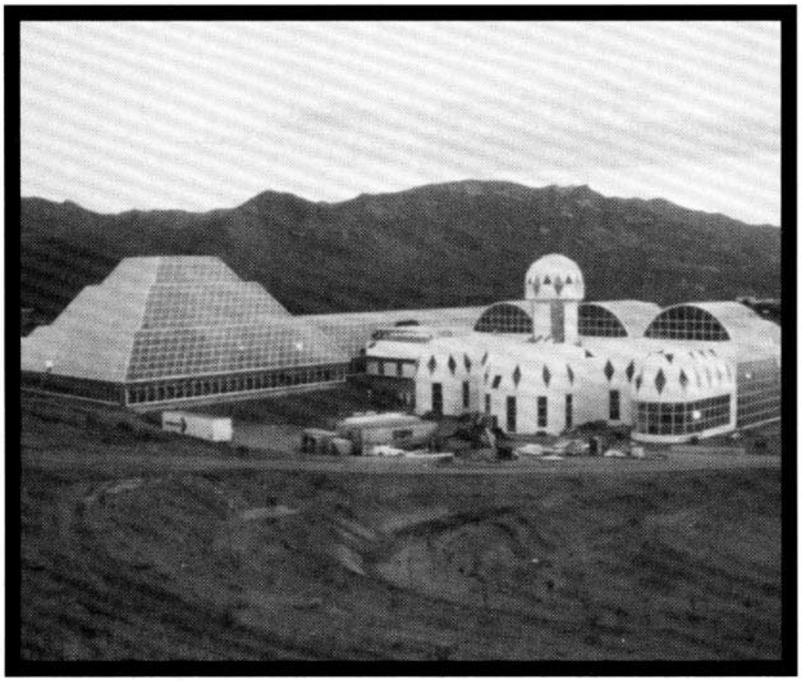
The architecture of the nerve system consists of five major levels:

- Environmental sensing and response (sensors and actuators),
- Local control and data acquisition,
- Supervisory monitoring and control of subsystems (G2-based expert system)
- Telecommunications, and
- Global monitoring, which includes the following:
  —Process Variable Monitoring System (PVMS) (G2-based expert system),
  —Network Monitoring System (NMS) (G2-based expert system),
  —Historical Archive (Oracle relational database system),
  —Medical laboratory information system,
  —Analytical laboratory information system,
  —Energy optimization (G2-based expert system),
  —Information analysis, management, and reporting.

Each biome's climate is controlled by an autonomous, dedicated HP9000/375 computer running a G2-based expert system called the Biome Supervisory Controller. These distributed control systems are monitored by two other G2-based expert systems—the Process Variable Monitoring System (PVMS) and the Network Monitoring System (NMS). Running on a Sun Sparc 2, PVMS monitors several environmental key indicators, including carbon dioxide levels, light, temperature, humidity, air flow, water flow, pressure, and ocean water quality. NMS, running on a HP9000/375, monitors all computer, data acquisition, and control systems on the network, including file systems, semaphores, shared memory, message queues, control and data acquisition processes, network traffic and health, system security, system load, log files (both system and application) and hardware status flags. Water quality is tested using a fully automated Process Ion Chromatograph, with a record of all tests being stored in the historical database system.

If any one of the monitored parameters should reach precarious levels, a graphic alarm icon is displayed on a geographic map of Biosphere 2 (located in the mission control center and the habitat where the Biospherians will live), indicating the approximate location of the system or sensor in alarm condition. There a text message describing the condition is displayed, and, if a serious problem exists, a radio message is broadcast to all researchers inside Biosphere 2 and personnel in mission control. PVMS and NMS are capable of displaying the rules used to infer the alarm condition, thus assisting personnel in determining the root cause of the condition.

Primarily, G2 is used for environmental control and monitoring. However, several other applications areas are being researched, including laboratory instrument control, energy optimiza-



The Biosphere 2 Structure in Oracle, Arizona

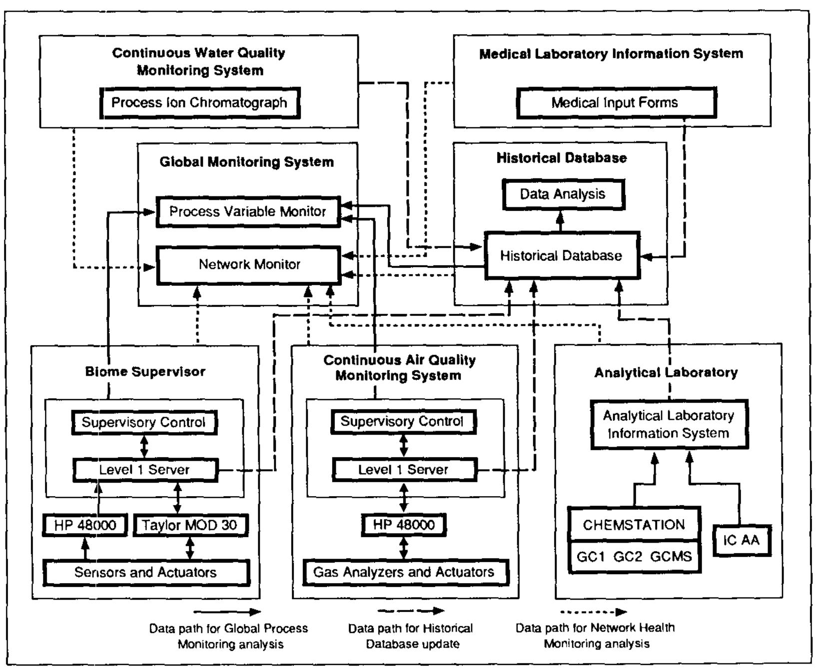


FIGURE 1.
Nerve System Architecture

tion, environment simulation, nutrient diet planning, and crop production scheduling. A G2 knowledge base which controls an instrument for continuously testing air samples (Continuous Air Quality Monitoring System) from different locations in Biosphere 2 is currently in the test phase and will be ready for operation when Biosphere 2 is sealed. Another knowledge base that attempts to minimize the energy input into the Biosphere 2 air-handling units based on the sensible and latent heat loads on each biome is currently in the design phase.

G2's ability to reason about classes of objects (eg., air-handling units, pipes, computers, water tanks, sensors), focus on rule sets, and perform both forward and backward chaining, have contributed to its usefulness in the implementation of the Nerve System. The graphics interface has made it possible to provide a flexible, user-friendly system with graphic icons displaying real-time process details and alarm states. The two G2-based monitoring systems make up the primary human interface to the Biosphere 2 Nerve System at the global level. C

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