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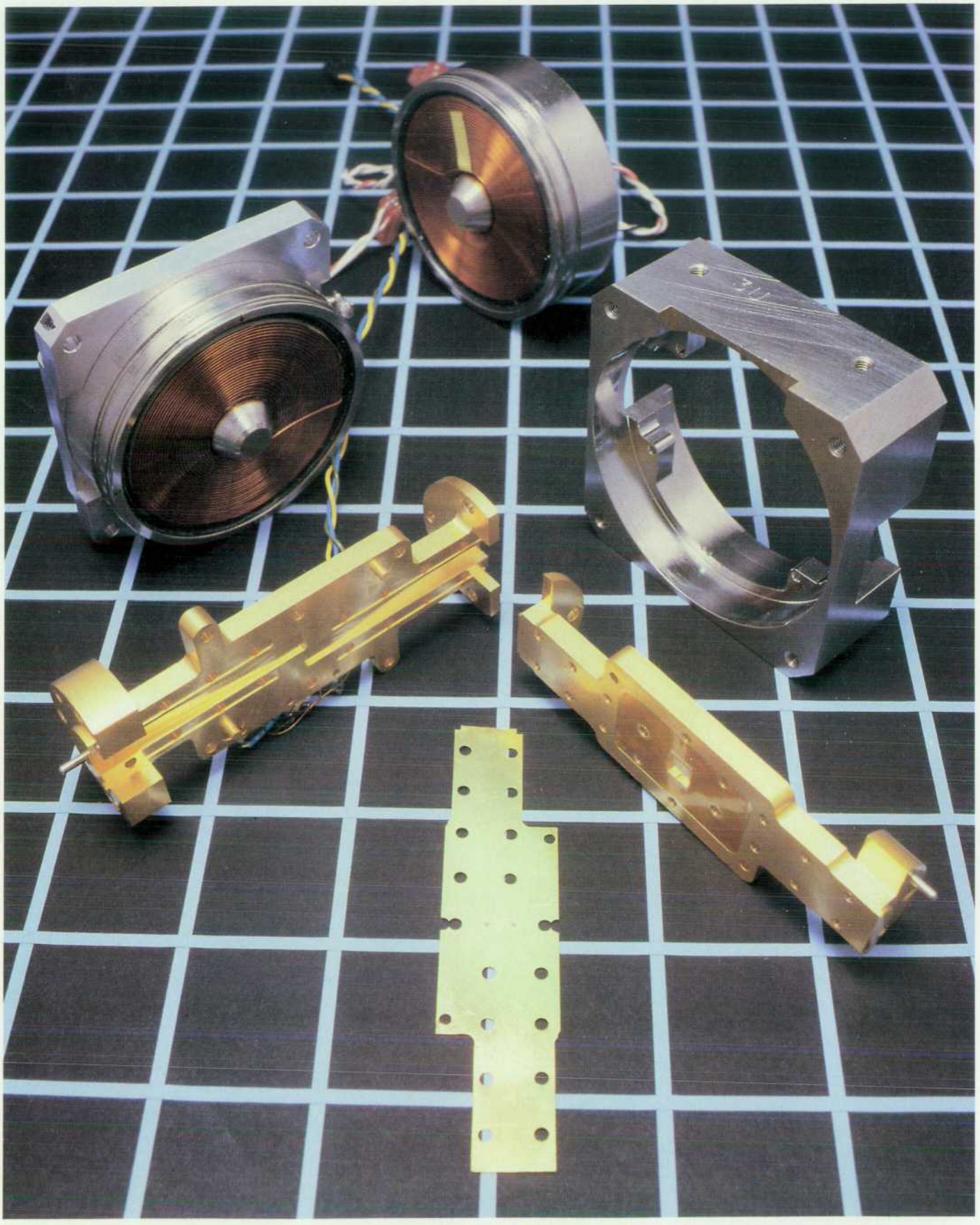

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Research Reports

Departments

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In this Issue

Our cover subjects this month can barely be seen in the cover photograph. They're the two tiny specks in the middle of the flat plate in the foreground. They are spheres of barium ferrite that serve as the frequency-sensitive elements of magnetically tunable bandpass filters for the millimeter-wave frequency range. (The millimeter-wave range is the region of the electromagnetic spectrum from about 30 to about 300 gigahertz. It's becoming more important as radar, communications, and other systems move to higher frequencies seeking higher performance or less crowding.) These filters are used as preselection filters in the HP 11974 Series preselected mixers, a family of four mixers designed for down-converting millimeter-wave signals from the 26.5-to-75-GHz range into the frequency range of compatible HP spectrum analyzers. The preselection filter removes unwanted image and multiple responses, natural consequences of the mixing process, that clutter the spectrum analyzer display and obscure the desired response. In the microwave frequency range, below 30 GHz, yttrium iron garnet (YIG) spheres have been used as resonators in such filters, but at higher frequencies, tuning magnets for YIG spheres begin to pose design problems, so a new material was needed. A new four-sphere filter design was also found necessary to achieve the required performance. The design and performance of the HP 11974 Series preselected mixers are described in the article on page 49. The article on page 59 gives the reasons for the choice of scandium-doped, M-phase barium ferrite for this application and tells how the spheres are made.

Software for computer integrated manufacturing (CIM) is in great demand, and HP development laboratories are responding with a steady stream of new products. Two are featured in this issue. The first, HP Interactive Visual Interface, or HP IVI, uses object-oriented design, the industry-standard X Window System, and widget technology to help application software developers provide graphical user interfaces for industrial applications. (Widgets are standard pieces of software that produce pushbuttons, scrollbars, and the like on computer screens.) HP IVI improves its users' productivity in designing user interfaces because it is interactive, facilitates saving and reusing interfaces, and doesn't demand that users know the details of the X Window System or widgets. The article on page 6 gives an overview of HP IVI, which consists of two main parts. Users construct their interfaces using HP IVI's interactive editor, described on page 32, and then activate the objects created with the editor by writing C-language programs using a toolkit of functions provided by HP IVI's application program interface. Details of the application program interface's object-oriented toolkit are in the article on page 11, and the design of the application program interface is the subject of the article on page 21. In the article on page 39, we're told how the HP IVI editor's own user interface was refined and given a 3D appearance with the help of a team of industrial designers.

The other CIM software product in this issue is HP Device Interface System, or HP DIS. It addresses the problem of efficiently developing interfaces between computers and factory-floor devices like robots, programmable controllers, and machine tools. This is a problem because these devices typically come from many manufacturers and have different, proprietary interfaces. HP DIS is a toolkit that helps application software developers create and test interfaces between HP 9000 computers and factory-floor devices. Its development facility provides a high-level language for specifying communications protocols. Its testing facility provides a test generator, a test exerciser, and a device simulator that makes it unnecessary to have actual devices to test interfaces. The HP DIS run-time facility executes protocols in real time. The design and performance of HP DIS are described in the article on page 62.

Simulation is an important part of many design processes because it makes it possible to refine a design without actually building anything, provided that the computer model used for simulation accurately reflects the behavior of the device or system being designed. Engineers at HP's Colorado Integrated Circuits Division wanted to verify the accuracy of the electrical models of a 408-lead multilayer ceramic package for a large integrated circuit chip. The models were made up of discrete inductances, capacitances, and resistances. To verify the models, these parameters had to be measured on a real package. When traditional high-frequency measurement methods proved inadequate, new methods were developed. These methods are the subject of the paper on page 73.

In integrated circuit design, the objective of simulation is sometimes to predict, in the design phase, the statistical distributions of a circuit's performance parameters in production. A problem is that IC parameter variations aren't all completely random, as they are assumed to be by commercially available circuit simulators. Those within a chip, such as side-by-side resistor values, are highly correlated, and failure to take this into account leads to inaccurate simulations. In the study reported in the paper on page 78, this problem was solved by applying principal component analysis, a branch of multivariate statistics. Each circuit parameter was expressed in terms of a set of independent random variables. The independent variables were then used as the inputs to the circuit simulator program, and the results were later converted to circuit parameter data.

Another application of simulation, this time to predict the pressure drop and air flow characteristics in a computer system processing unit, is described in the paper on page 82. In the past, these quantities have been determined from measurements on prototype machines, which are available only after most of the design has been done. If the measured results are unacceptable, major design changes may be required. The study showed that, using supercomputers and finite element modeling, it is possible to simulate the air flow accurately enough to allow meaningful decisions early in the design phase.

R.P. Dolan
Editor

Cover

The flat plate in the foreground is the iris plate from a magnetically tuned preselection filter used in the HP 11974 Series preselected mixers. In the middle of the plate are two tiny barium ferrite resonator spheres. Also shown are the top and bottom halves of the tuning magnet, the magnet body, and the two parts of the waveguide assembly.

What's Ahead

In the December issue, we'll have articles on the autochanger and servo design and system integration of HP's 20-Gbyte rewritable optical disk library system, designed for direct access secondary storage. Error correction, software protection, and system integration of HP's CD-ROM drive will also be featured. The data communications and terminal controller for HP 3000 computers running the MPE XL operating system now supports X.25 network packet assembler/disassemblers; two articles will deal with this capability. We'll also have a research report on anisotropic dimensional changes in cold-drawn copper beryllium alloy as a result of aging.

An Overview of the HP Interactive Visual Interface

The HP Interactive Visual Interface (HP IVI) product uses object-oriented and window technologies to provide interactive and programmatic tools for building graphical user interfaces.

by Roger K. Lau and Mark E. Thompson

IN THIS AGE OF INFORMATION, creating effective user interfaces for industrial automation applications is a greater challenge than it has ever been. The right details from a vast array of information must be shown in the appropriate form to the intended group of viewers. In addition, the information that is communicated must be conveyed in such a manner as to enhance the decision making process. It often takes more time to develop the interface than it takes to develop any other part of an application. HP Interactive Visual Interface (HP IVI) is designed to help developers provide the type of user interface needed for industrial applications.

HP IVI is a user-interface development tool built on the X Window System Version 11 and runs in the HP-UX operating system environment. It consists of two main parts: an interactive editor (HP IVIBuild) and an application program interface (API). Users construct their symbols and displays with HP IVIBuild (the builder) and write a C program using the API calls to call up and activate the windows and other objects created with the builder. An application's user interface can be constructed without the assistance of HP IVIBuild, but with it productivity is greatly increased by the ability to create the interface interactively. HP IVI is also one of the few products to combine at the builder level the power of a graphical presentation with the flexibility and interactivity of widgets (e.g., pushbuttons, scrollbars, and toggle buttons).[1]

This article describes some of the market research and the target customers for HP IVI, and provides an overview of the two main components of HP IVI, HP IVIBuild and the application program interface.

Market Research

The main customers of HP IVI are software engineers who build industrial applications. This includes system integrators, independent software suppliers, and end users with internal software engineering groups. These users benefit by being able to customize screens to their customers' applications and by being able to reuse the symbols they created and saved in previous applications. HP IVI also buffers its users from having to know the details of the intrinsics of both the X Window System and widgets. This is considered to be a benefit and a boost to productivity.

Market research indicates that manufacturing applications require graphical user interfaces, and the use of graphics on the factory floor is growing and being applied to monitoring production processes and data gathering. The requirements are performance, reliability, and the integrity of data from a workcell. To satisfy these demands, the HP IVI product:

- Minimizes the user's expense for the development of user interfaces
- Provides a distributable user interface for improved cost, performance, and flexibility
- Offers windowing functions and dynamic data configuration
- Integrates graphics and widgets intelligently
- Gives software engineers the productivity boost needed for them to remain competitive
- Ensures top performance and reliability
- Gives the user full control over data from the factory floor
- Builds on standards.

Early in the project, the HP IVI project team used a technique called quality function deployment (QFD) to help analyze customer needs in the industrial automation area. This research helped to define the features for HP IVI. The box on page 9 provides more information about QFD and its use by the HP IVI team.

HP IVIBuild

HP IVIBuild is the interactive window and symbol build-

(continued on page 8)

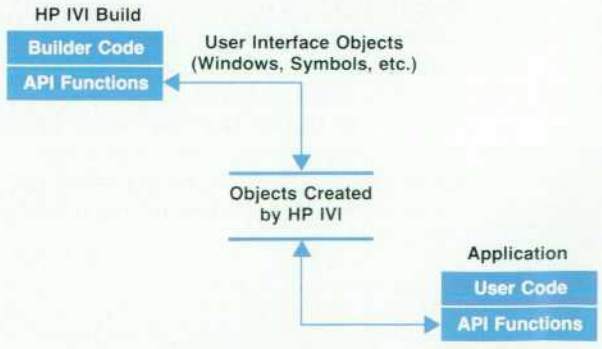

Fig. 1. *HP IVIBuild is used to create user interface objects that are saved in a file, and a user application uses the API functions to retrieve and manipulate the objects.*

HP IVI Project Management

The HP Interactive Visual Interface project was a relatively large software project (100 KNCSS) and as such it was faced with some interesting challenges during product development. Besides the normal challenges associated with software project management (e.g., version control, code inspections, project standards, and schedule deadlines), HP IVI was faced with three main challenges: determining the exact customer needs before design and implementation, using existing software, and using new software development technologies. For determining customer needs, a process called quality function deployment (QFD) was used. This process helped us to determine the feature set for HP IVI (see box on page 9). The existing software was a combination of software from other HP entities and from outside vendors. Finally, the new technologies included the use of objects and windows for design and implementation.

Existing Software

One of the primary goals of HP IVI was to leverage the work of others. The decision to use existing software resulted from the desire to decrease the time to market for the product by reducing the engineering time and effort involved in design, implementation, and support. There was also a need to base HP IVI on components that conform to standards (explicit or de facto). To these ends, the basic framework of HP IVI is based on software that was purchased as well as software that was produced by other entities in Hewlett-Packard.

The HP IVI project team realized the benefits that could be obtained by leverage early on. The basic object-oriented framework, the error handling routines, the X11 client library and server, the X toolkit, and the HP X widget set were all the work of others. While we certainly achieved our goals of reducing design, implementation, and support costs, we missed our original time-to-market goals.

Following are some of the lessons we learned about leveraging existing software.

- The quality and stability of existing code is a critical factor. If there are many defects in this code, much time will be spent isolating the problem and negotiating with the software supplier to have it repaired. This can wreak havoc with a project schedule. One way around this is to obtain the source code for the underlying software and make the repairs locally. This may provide the most timely solution, but also raises many supportability questions.
- Negotiating enhancements to the existing software may be difficult. Priority lists may not mesh well between vendor and receiver. Important enhancements in the underlying software may be delayed because of this.
- Performance of a product may be adversely impacted by existing software. If this is the case, lobbying for improvements may be time-consuming and marginally successful.
- Good documentation of existing software is essential for a product to be successful. Inadequate or inaccurate documentation can also impact schedules.
- It is very important to establish a good line of communication and a strong working relationship with the existing software supplier. Changes made to their product may have drastic effects on the local product. It is important to learn about changes as early as possible (i.e., at the investigation phase rather than at the release phase).

Project teams that leverage a large amount of software from other sources should be very careful not to assume that leveraging means that less attention can be paid to producing a very detailed design. Leveraging software does not mean there is no cost associated with it. Engineers have to learn and understand the code, design impacts must be assessed, and the leveraged code must be supported over the life of the product. Also, leveraging product components does not automatically ensure a faster time to market.

New Technologies

HP IVI is an object-oriented system that is based on the widget technologies and the X Window System. Through the QFD process we found that building on a standard software platform is viewed as an important requirement by our target market.

At the start of the HP IVI project no one on the team had any experience with object-oriented programming and design and only one person was familiar with window systems. Therefore, we had to develop a process to disseminate technical information and promote technical expertise among the project team very quickly. This was accomplished through training, the exchange of information during design and code reviews, and the simple sharing of expertise among the project team.

The following observations come from our experience with object-oriented programming and design:

- Careful consideration should be given to mapping object classes to source code files. The consequences can be frequent file access conflicts when changes are made to a file.
- The temptation to redo class hierarchies should be controlled. Developers must be careful to make practical choices on when the class hierarchies are sufficient.
- First-time users should not expect magic. We believe that there was a significant learning curve involved in our decision to use object-oriented programming and design.
- Once the learning curve is overcome, the object paradigm is a natural and productive one to use for developing software products.
- Object-oriented programming and design have a technical jargon that might mystify developers and their managers at first. Therefore, familiarity with and consistent use of terminology must be established at the start of the project.
- The object paradigm is not applicable to all software engineering projects. Knowing when to reject this technology in favor of a procedure-based design is important.

The use of multiple new technologies in a project with few team members having experience in any of these technologies does have its problems and can be a significant factor on the schedule because it is difficult to anticipate problems and avoid pitfalls. However, using new technologies on a project can be a significant motivator to the engineering staff. Benefits and risks of the inclusion of new technology in any product development effort must be weighed carefully.

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er of HP IVI. It is an API application because it uses the HP IVI API library of C functions to handle both the visual and the nonvisual aspects of creating objects such as managing object data structures and performing operations required to manipulate objects. Consequently, the windows and models created and saved by the builder can be restored by an API program and vice versa (see Fig. 1). For the most productive use of HP IVI, the user first creates the windows needed by an application using HP IVIBuild and then mobilizes the created windows using a C program containing API functions. Fig. 2 shows an application user interface being created with HP IVIBuild. Although an entire HP IVI application could be written using just the API C functions, HP IVIBuild provides the following advantages over this method:

- No initial programming is required.
- The user can look at the user interface and manipulate it while creating it.
- The interface can be altered very quickly.
- Several graphical conveniences are available such as snapping to a grid and a simple method of creating ellipses.
- An API program that uses HP IVIBuild-created objects is much simpler than one that creates the same objects from scratch.
- Symbols created in an HP IVIBuild session can be saved and reused.

The articles on pages 32 and 39 provide more information about HP IVIBuild.

Objects and API

Since HP IVI is an object-oriented system, all operations are done with objects, resulting in a system that is a hierarchy of objects. Building this hierarchy starts with creating window objects (windows on the display) and then placing graphics and widget objects into the windows. To activate the objects in the window (i.e., give them dynamic properties) some of the attributes of the objects can be changed (e.g., foreground or background color, visibility, or fill percentage for a rectangle). When an application uses objects to display data values, it can make calls to the API functions to update the data values in the objects displayed in the windows.

The objects used in HP IVI are categorized into four hierarchical layers:

- High-Level Objects. These objects specify global attributes for the other levels of objects. This level includes the window and model objects mentioned earlier.
- Composite Objects. These are organizational groupings of primitive objects. This includes menus and their component menu panes, row-columns, and scroll lists.
- Primitive Objects. These are basic widgets and graphics objects—the basic visual pieces that make up the display. Graphics primitives include items such as polylines, splines, arcs, rectangles, and circles. Widget primitives include pushbuttons, toggle buttons, text widgets, text-edit widgets, menu buttons, and scrollbars. Both types of primitive objects can receive input from the user.
- Low-Level Objects. These are mostly nonvisual objects that are used to specify certain object attributes. Objects that handle object data structures and objects that handle events are examples of low-level objects.

Because an object hierarchy is used, displays can be created from the top down (parent to child) or the bottom up (child to parent), giving the designer a lot of flexibility in implementation. Certain objects can be gathered and arranged by making them into children of composite ob-

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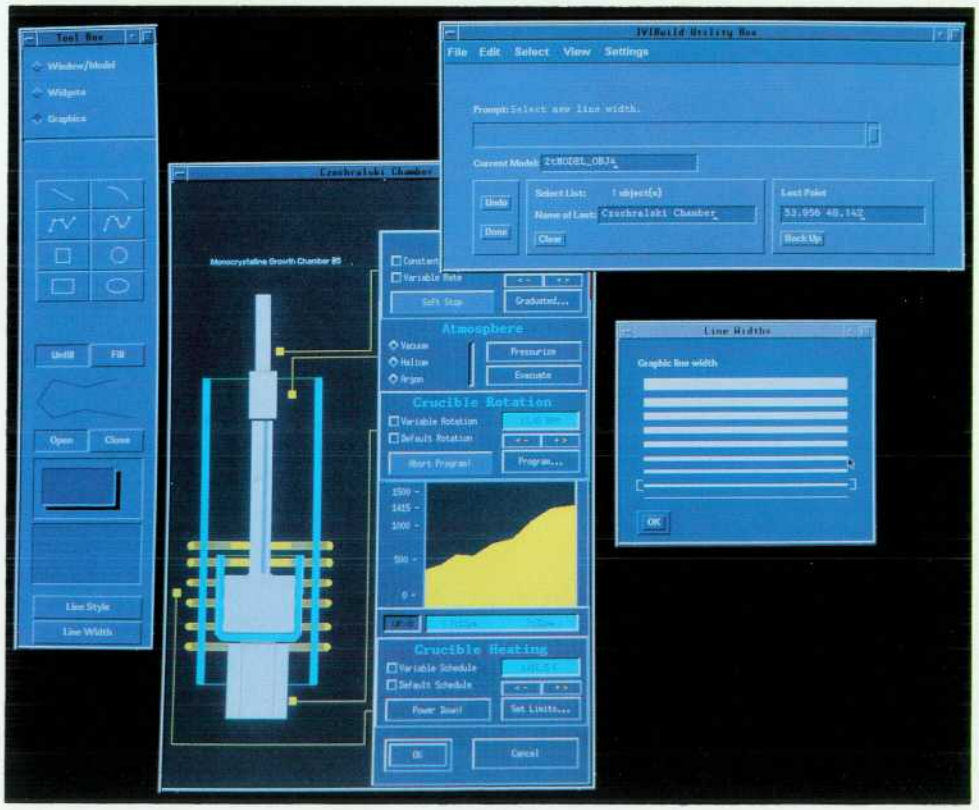

Fig. 2. *An application user interface being created using the interactive tools provided by HP IVIBuild. The tool box, utility box, and line width panels are HP IVIBuild components.*

Quality Function Deployment and HP IVI

Quality function deployment (QFD) is an analytical method of collecting and analyzing subjective and objective data about customer needs and wants. It is one of the methods the HP IVI project team used to determine the minimum feature set required by our target customers. QFD was chosen because it facilitates not only the translation of customer wants and needs into product features, but it also enforces consideration of methods to implement the features. When the features are known, the project schedule and required resources can be properly planned. Since our organization (HP's Industrial Application Center (IAC)) was new, it was easy to promote QFD as a viable technique because there were no traditions ingrained in the organization.

The QFD process is shown in Fig. 1. The first step is to collect the customer needs data. To get this information we visited many of the customers who represent our target market. This took place over a period of about two months. IAC teams of two or three members went out to each customer site. Team personnel came from marketing, R&D, and management. These teams presented a broadly defined, theoretical product to each customer, focusing on how the product could make them more successful. To get the spoken and latent needs out, a loosely structured, open-ended questionnaire was presented as an aid for generating discussion. Notes were taken to record as much data as possible. The idea behind this technique was that some people don't state their feelings directly. They might say, "Forms based applications are good...if you have to use a terminal." But, what they really mean is, if given a choice, they wouldn't use a terminal at all for that application.

Once the data was collected it was time for analyzing. We formed teams with people from the HP IVI project, marketing, and several people from outside IAC. Some of these people included learning and human factors specialists and a user interface developer from another division. One other person was our QFD consultant.

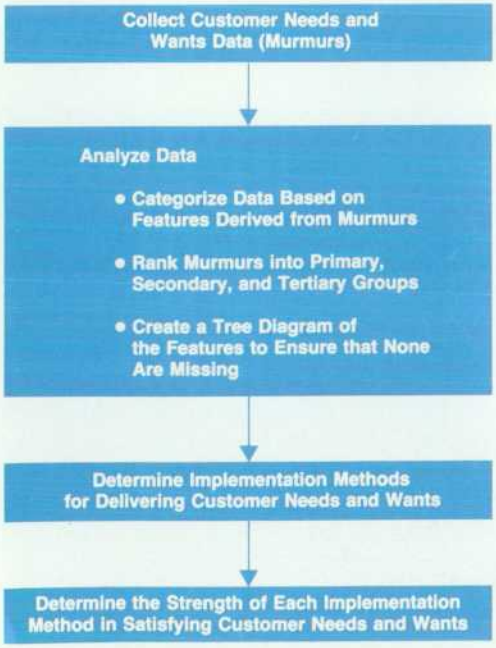

Fig. 1. *The QFD process.*

Customer needs, which we called *murmurs*, were categorized into groups based on some desired customer feature related to issues such as ergonomics or performance. When we finished categorizing the murmurs, each murmur was ranked into primary, secondary, and tertiary needs. Each of these rankings represented a translation of customer needs into quantifiable technical terms. An example of customer murmurs and the rankings is shown in Fig. 2. In most cases we had to derive the secondary or tertiary need. From here the features were placed on a tree diagram to ensure that there were no gaps, and to guarantee that we had met all of our customer needs.

During data collection, each of the customer needs should be given an importance rating. However, our collectors had not been trained before going to the customers and so they did not collect the importance rating with the murmurs. The team assigned the ratings during analysis.

The next step was to develop methods for delivering customer needs. This was done with knowledge of what could be done with software. These became our implementation methods. For example, if a customer needed a window to display alarm information quickly, this translated into choosing a system that could rapidly retrieve and display data in windows, such as the X Window System.

Each implementation method was analyzed to determine if it had a strong, medium, or weak relationship to satisfying customer needs. This formed the relationship matrix (see Fig. 3). Symbols are used in the matrix to indicate the relationship between customer needs and implementation methods. If no symbol is placed on the matrix then the implementation has no relationship to satisfying customer needs. This graphic representation is very useful. One can look at the matrix and see the areas that cover the customer needs and the areas that require more attention because they have little or no coverage. This task is the most labor intensive portion of the QFD process.

To get the features for the first and second release of HP IVI from the matrix, we assigned a number to each cell. For each feature we summed the cells to get an idea of how effective the feature would be at meeting the customer needs. We selected a cutoff value to determine the set of features that would bring us the most return for our investment in engineering time and effort.

QFD proved to be an excellent tool for product definition. The feature set that was established for HP IVI has generated much customer interest. One of the most significant benefits from this

Primary	Secondary	Tertiary
Must Have Good Performance	Screens Come up Fast	2 to 3 Seconds
	Many Symbols on Screen	10 to 20 Seconds
Must Have Good Ergonomics	Pictures not Text	Icons
Forms Entry Needed	Must Have Range Checking for Data Entry	

Fig. 2. *A sample of customer needs and wants (murmurs) ranked in primary, secondary, and tertiary order.*

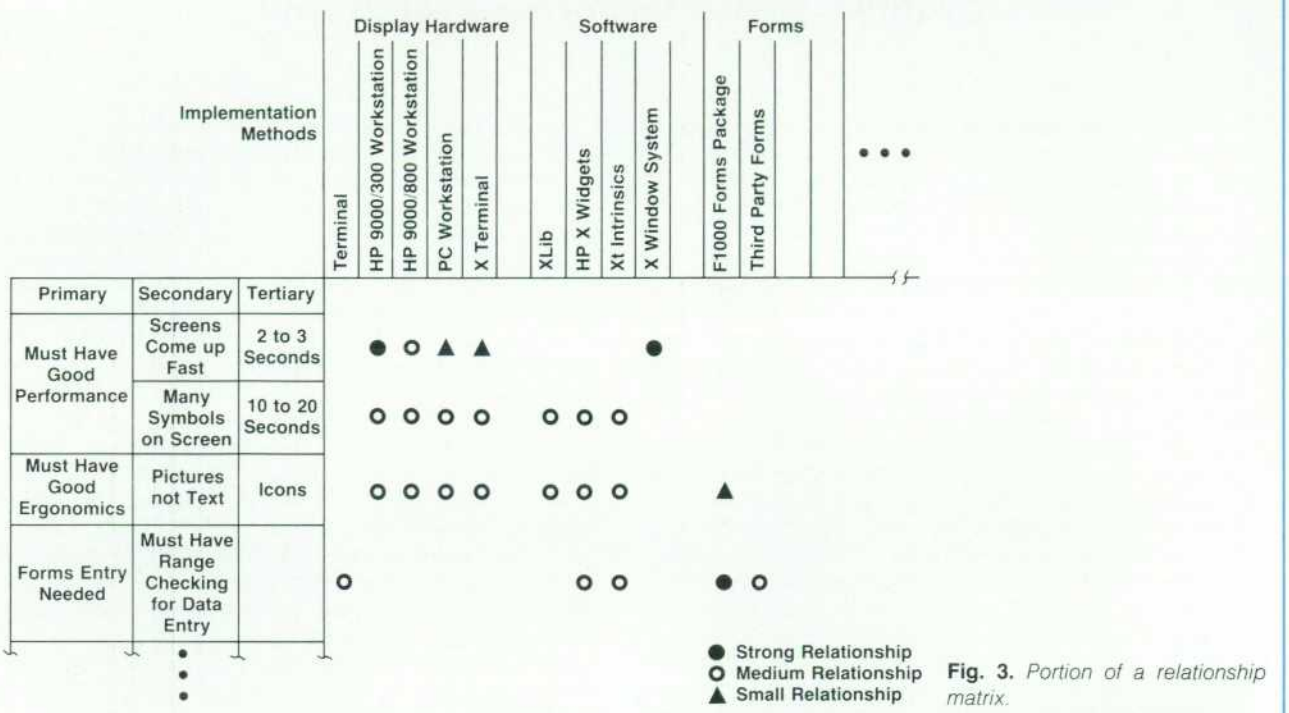

Fig. 3. *Portion of a relationship matrix.*

process was that because the engineering team was involved in this process, they emerged with a much better understanding of what the users really wanted.

Knowing when to stop the QFD analysis is important. Unless specific goals and targets are set, overanalyzing can waste valuable project time. Establishing a set of musts and wants to be accomplished with QFD, and drawing clear boundary lines early in the investigation phase, helps keep the analysis from bogging down in too much detail. Also needed are tools to support the technique. The HP IVI team did most of the data analysis manually and as a consequence the data has not been updated as often as might have been done if the data could be manipulated electronically.

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jects. Composite objects can be used to organize and add extra control over their descendant objects. For example, a row-column object can be used to organize different widget primitives into rows and columns.

All objects in the hierarchy have attributes (e.g., color, size, shading, etc.). It is through the control of these attributes that the displays created with HP IVI get their dynamic quality. One can easily manipulate several attributes on an object with a single API function call, changing location, color, visibility, or some other attribute. Other API function calls enable the developer to:

- Create and free objects
- Manipulate object attributes
- Save and restore objects
- Locate objects
- Obtain user input from primitive objects
- Perform visual updates of the display
- Manipulate lists of objects.

As an example, callback objects can be attached to any visual object and cause a callback function to be called whenever a predefined event (such as clicking on the mouse button or depressing a key on the keyboard) occurs. The callback function can be used to obtain and manipulate data from the shop floor and modify attributes of objects on the display (e.g., changing an object's color from green to red or changing the textual information displayed in an object). The API functions and the internal design of these functions are described in the articles on pages 11 and 21.

Conclusion

HP IVI facilitates the design and implementation of one of the most important parts of any manufacturing application—its interface to the user. The benefits of the windowing technology of X11 are just beginning to be realized on the manufacturing floor. HP IVI is one of the first integrated applications to bring the X Windows technology to the factory floor. The combination of widgets and graphics gives the application designer more freedom to present the needed information in the fashion best suited for its intended viewers. This design freedom promotes the kind of informed decision making needed in today's fast-paced and highly competitive industrial marketplace.

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The HP IVI Object-Oriented Toolkit

Using object-oriented design techniques, a minimum set of functions is provided with the HP IVI product for manipulating widgets and graphic objects to create a graphical user interface.

by Mydung Thi Tran and David G. Wathen

THE HP IVI APPLICATION PROGRAM INTERFACE (API) is an object-oriented toolkit of C functions that enable a software developer to create an interactive and informative graphical user interface programmatically. The API functions can be used for any application in which a highly interactive graphical user interface is required. The collection of API functions provides the ability to build different models of user interfaces that can be saved and used again in other user interfaces. High-level objects provide the control and organization necessary to support lower-level composite and primitive objects. All objects have configurable attributes or characteristics that make it possible to customize the look and feel of a particular object. Color, size, and font are a few examples of these attributes. The API functions allow a programmer to do things like create and free objects, query attributes, save and restore objects, get input, and find objects by location.

This article describes the the API functions and the article on page 21 describes the internal design supporting these functions.

The API Object Hierarchy

All the components of an API application are separate objects that are combined together in a hierarchical arrangement to form a working user interface. An example of this hierarchical relationship is shown in Fig. 1. This relationship is described in terms of ancestry. For instance, Model 12 in Fig. 1 is the parent of three children: Model 21, a rectangle, and a row-column object. Another way of saying this is that Model 12 is the ancestor of three descendants: Model 21, a rectangle, and a row-column object.

Every API object belongs to one of four groups: high-level objects, composite objects, primitive objects, or low-level objects. Fig 2 lists the different API object groups.

High-Level Objects. These objects control and organize groups of objects and hold global resources that help define other objects in the hierarchy. The high-level objects must be created in a specific order: system object, server object, window objects, and model objects. Before anything can be displayed, at least one of each of these objects must be available. Since these objects are required for every application, the API will create default high-level objects if they are not explicitly created.

The system object is the highest object in the API object hierarchy. This object stores global attributes that affect the input loop, the update pass, and global resources. The input loop is composed of the code that handles user input and an update pass is the process of flushing changes to the display. There can only be one system object per application. All other objects (except low-level objects) are descendants of the system object. The direct descendant of a system object must be a server object.

A server object is the interface to the display system. Information regarding the display and its physical characteristics is stored in this object. The server object establishes the link between the display device (an X11 server) and the user application (the client). Just like the system object, there can only be one server object per application. Windows are the only children of the server object.

Window objects represent the drawable region of the display. A window is an area on a display that connects the world coordinate system (e.g., inches, mm, etc.) defined for a window to the device coordinates (i.e., pixels) of the display system. The window can be seen as a viewport into the world coordinate system. An application can have any number of windows. They can overlap one another and they can be manipulated using a window manager or

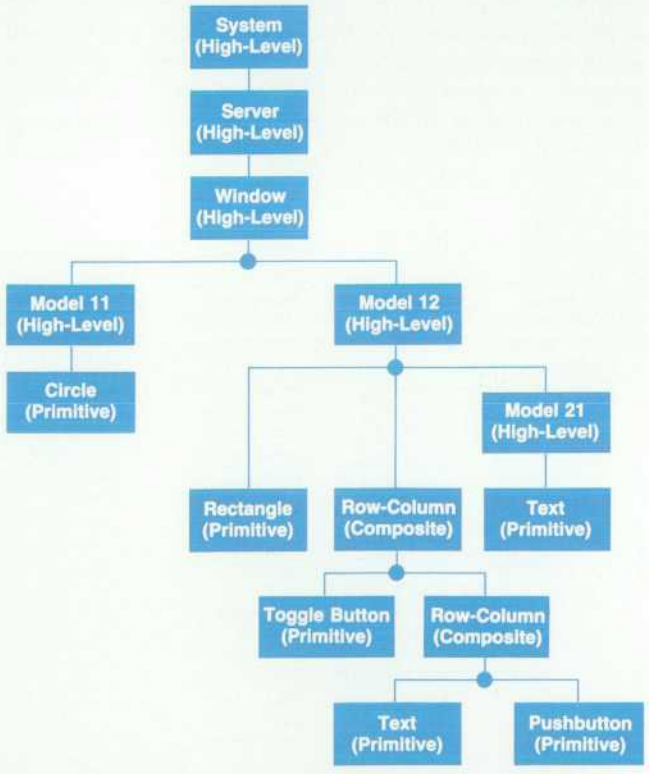

Fig. 1. *The API object hierarchy of a simple application.*

the API functions. The last high-level object, the model object, is the only valid child of a window object.

The model object allows an application to put composite, primitive, or other model objects into a single group or collection. When these objects are grouped together, functions can be performed on them as if they were a single object. At the same time, each part will retain its individuality. Models can represent a symbol or template that can be saved and restored as many times as desired. Models can have other models, composites, or primitive objects as children.

Primitive Objects. These are basic visual objects that are part of one of two categories: graphic primitives or widget primitives. The graphic primitives are visual objects (e.g., circles, rectangles, and arcs) that can receive mouse input. An application can use these objects for graphically representing user-oriented objects that display crucial information such as liquid levels and temperature. The widget primitives (e.g., pushbuttons, scrollbars, and text edits) are also visual objects. However, unlike the graphics primitives, widget primitives can receive keyboard input as well as mouse input. The widget primitives are used for display, text editing and input, and selection capabilities. Primitive objects have no children.

Composite Objects. These objects provide the means to organize and manage other objects. Specifically, composite objects make it possible to group primitive widget objects and other composite objects so that they can be manipulated as a single object. A function or attribute specified for a composite object affects its children without actually changing them. For example, erasing or redrawing a row-column object will cause all its children to be erased or redrawn automatically.

Low-Level Objects. These are objects that are not directly visible like primitive or composite objects. They are standalone objects that are used to specify attribute values for primitive, composite, or high-level objects. Low-level objects are used to set attributes for the other three object groups, apply API functions to a list of objects, or deal with user input from the activated objects.

High-Level Objects	Composite Objects	Primitive Objects	Low-Level Objects
System Server Window Model	Menu Menu Pane Row-Column Scroll List	Widgets: Image Menu Button Pushbutton Scrollbar Text Text Edit Toggle Button Graphics: Polyline Line Rectangle Square Circle Ellipse Arc Spline Text Label	Callback Color Font Raster Input Data List Point Transform

Fig. 2. *API object groups.*

Polymorphism and API

One of the key features of object-based systems is the concept of polymorphism. Polymorphism allows different objects to share a common operational interface (operations with the same name). When an operation is invoked, the function dynamically determines the object type and executes the appropriate code. Object-oriented programs are polymorphic because they can operate on many different object types with the same functional interface. This common interface provides a great deal of flexibility and ease of use to the API programmer. Common access reduces the number of functions and increases the power provided by the basic set of functions.

The API functions provide the functionality of polymorphism through an identifier called ZtId. When an object is created via the ZtCreate function, a ZtId is returned from the call for use in further operations. The ZtId is a pointer to the object that was just created. This handle allows the programmer to reference the object when additional modifications are necessary. The API functions use this identifier to determine the type of object being manipulated.

Attributes and Arglists

Associated with API objects are attributes that describe properties of these objects. Examples of object attributes include properties that define appearance characteristics such as colors and fill patterns for graphic objects, and font, highlight area, and 3D shadowing for widget objects. There are also coordinate system attributes that control the position and sizing of objects, including their point, height, width, scale, rotation, and translation. Table I lists the categories of API attributes.

There is a specific list of attributes assigned to each API object type. Users can set these attributes to desired values or can query the values contained in them through a data structure called an Arglist. An Arglist is a variable-length array of attribute-value pairs. The following is the C structure declaration for an attribute-value pair.

```
struct ZtArgListStruct
{
ZtAttributeType ZtAttribute;
ZtValueType ZtValue;
};
typedef struct ZtArgListStruct ZtArgListItem;
/*where:                                          */
/*    ZtAttribute is the defined attribute        */
/*    ZtValueType is defined as a pointer to a    */
/*    variable containing the attribute value     */
```

Arglists are used to define attributes of objects or functions. Some of the advantages of using Arglists include:

- Arglists free users from fixed parameters in a function call. The number of attributes that the user can pass as parameters can vary.
- The number of function calls can be minimized by including multiple attributes in the Arglist as opposed to having to use one function call per attribute change.
- Attributes can be initialized in the Arglist either statically or dynamically (at run time).

Table I
Categories of API Attributes

Category	Description
General	Attributes that are common to most objects. For example, the object name (ZtNAME), an object's visibility status (ZtVISIBLE), and user data (ZtUSER_DATA).
Coordinate System	These are attributes that define: ■ Size and position such as an object's height and width (ZtHEIGHT and ZtWIDTH) ■ Transformation, such as an object's rotation, scaling, and translation characteristics (ZtROTATE, ZtSCALE, ZtTRANSLATE) ■ Normalized device coordinates for placing windows (ZtXMIN, ZtXMAX, ZtYMIN, ZtYMAX) ■ Aspect ratio of window device coordinates (ZtADJUST, ZtXADJUST, ZtYADJUST) ■ Aspect ratios of server objects (ZtXPIXELS, ZtYPIXELS).
Trickle-Down	Attributes that affect the descendants of objects (ZtVISIBLE, ZtSENSITIVE).
Color, Font, Raster	Attributes that specify the object's color, font, or raster. ■ Raster lists (ZtRASTER_LIST) ■ An object's color (e.g., ZtBACKGROUND_COLOR, ZtFOREGROUND_COLOR, etc.) ■ An object's font (ZtFONT) ■ An object's raster (e.g., ZtFILL_RASTER, ZtICON_RASTER).
Pattern and Line	Attributes that control the appearance of borders, lines, and fills (e.g., ZtFILL_TILE, ZtBACKGROUND_TILE, ZtLINE_WIDTH).
Widget Appearance	Attributes that define a widget's appearance (e.g., ZtSHADOW, ZtBOTTOM_SHADOW_COLOR, ZtTOP_SHADOW_ COLOR).
Callback	Attributes used to attach user-defined functions to an object. These functions are used to respond to user input. For example, ZtREASON specifies when a callback function should be called, and ZtCALLBACK_FUNCTION specifies a function for processing user input.
Parenting	Attributes that affect or define the current API object hierarchy (e.g., ZtCHILD_LIST, ZtCURRENT_MODEL).
Keyboard Traversal	Attributes that assign the input focus to an object (e.g., ZtTRAVERSAL, ZtNEXT_TOP_WINDOW).
Function	Attributes that affect the capabilities of functions (e.g., ZtRECURSIVE, ZtMERGE).

API Functions

Because of polymorphism a minimum number of API functions are required for manipulating API objects. Polymorphism allows the same API function to be used to handle more than one object. Table II shows the API functions available for manipulating the object groups shown in Fig. 2.

Table II
Categories of API Functions

Function Use	Function Names
Create and Free Objects	ZtClone, ZtCreate, ZtCreateList, ZtFree
Manipulate Attributes	ZtChange, ZtQuery
Save and Restore Objects	ZtSave, ZtRestore
Locate Objects	ZtFindByAttribute, ZtFindByLocation
Receive Input	ZtDo(..,ZtINPUT,..)
Perform Visual Updates	ZtDo(..,ZtDRAW,..) ZtDo(..,ZtERASE,..) ZtDo(..,ZtFLASH,..) ZtDo(..,ZtLOWER,..) ZtDo(..,ZtRAISE,..) ZtDo(..,ZtREDRAW,..) ZtDo(..,ZtUPDATE,..)
Manipulate Lists	ZtCheckListObject, ZtCountList, ZtGetListIndex, ZtGetListObject, ZtGetListTail, ZtInsertListIndex, ZtInsertListObject, ZtInsertListTail, ZtMergeListIndex, ZtMergeListTail, ZtMergeListObject, ZtRemoveListIndex, ZtRemoveListObject, ZtRemoveListTail, ZtReplaceListIndex, ZtReplaceListObject, ZtReplaceListTail
Manipulate Arglists	ZtFreeArgList

Create and Free Objects

Objects are created using the function ZtCreate. Any attributes that are required to be different from the defaults can be passed in the object ArgList when calling ZtCreate. For all the attributes not included in the object ArgList, the API will automatically set them to defaults. Once an object exists, multiple copies of this object can be made by cloning it with the function ZtClone. ZtClone also allows the users to alter some of the attributes of the newly cloned objects in the same call.

The following example shows the creation of two text objects with one fixed size, different text strings, and different positions on the display. Fig. 3 shows the data organization resulting from this example.

```
int return_val;
ZtId text1_Id, text2_Id, pointId;  /*  object identifiers */
/* arglist for text object (containing attribute-value pairs)  */
static REAL64 h, w;
static ZtArgListItem textArglist [ ] =
{
    ZtHEIGHT,       (ZtValueType)&h,    /*  text height          */
    ZtWIDTH,        (ZtValueType)&w,    /*  text width           */
    ZtPOINT,        (ZtValueType)NULL,  /*  ZtId for point       */
    ZtSTRING,       (ZtValueType)NULL,  /*  text string          */
    NULL, (ZtValueType)NULL
};
/*  arglist for point object                                     */
static REAL64 x, y;
static ZtArgListItem pointArglist [ ] =
{
    ZtX,        (ZtValueType)&x,
    ZtY,        (ZtValueType)&y,
    NULL,       (ZtValueType)NULL ;
}
    /*  create reference point for objects                       */
        x = 10.0; y = 10.0;
        pointId = ZtCreate(ZtPOINT_OBJ,pointArglist, NULL);


    /*  setup to create first text object with height = 20 and   */
    /*  width = 40                                               */
         h = 20.0; w = 40.0;
         textArglist[2].ZtValue = (ZtValueType) pointId;
         textArglist[3].ZtValue = (ZtValueType) "First text object";
    /*  create the first text object                             */
         text1_Id = ZtCreate (ZtTEXT_OBJ, textArglist, NULL);
    /*  change point components                                  */
         y = 60.0;
         return_val = ZtChange (pointId, pointArglist, NULL);

    /*  create second text object at (10.0,60.0)                 */
         textArglist[3].ZtValue = (ZtValueType) "Second text object";
         text2_Id = ZtCreate (ZtTEXT_OBJ, textArglist, NULL);

    /*  free point object if it is no longer needed              */
         ZtFree (pointId, NULL);
```

Instead of calling ZtCreate twice, the function ZtClone can be used to create the second text string object:

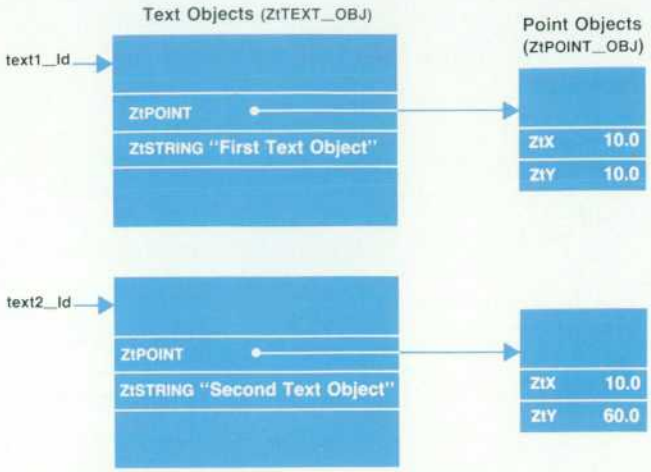

Fig. 3. *Data organization for text objects created with the function* ZtCreate *or* ZtClone.

```
int return_val;
ZtId text1_Id, text2_Id, pointId; /* object identifiers*/
/*  arglist for text object (containing attribute-value pairs   */
                .
                .   The text Arglist and the point
                .   Arglist are the same as in the
                .   previous example.

/*  arglist for cloned text object                               */
    static ZtArgListItem cloneArglist [ ] =
{
    ZtPOINT, (ZtValueType)NULL,
    ZtSTRING, (ZtValueType)NULL,
    NULL, (ZtValueType)NULL
};
                .
                . The reference points and the first
                . text object are created the same as
                . in the previous example.

/*  create the second text object at (10,60) using the           */
/*  ZtClone function                                             */
    y = 60.0;
    return_val = ZtChange (pointId, pointArglist, NULL);
    cloneArglist[0].ZtValue = (ZtValue Type)pointId;
    cloneArglist[1].ZtValue = (ZtValueType) "Second text object";


    text2_Id = ZtClone (Text1_Id, cloneArglist,
    NULL);
    .
    .
    .
/*  free point object if it is no longer needed                  */
    ZtFree (pointId, NULL);
```

ZtClone is particularly useful for models and composite objects. With one call, the model or the composite object and its descendants can be duplicated. A call to ZtClone can be modified to control the depth of cloning for a list of objects. In the following example there are two model ob-

jects that have identical properties except for the background and foreground colors. The first model object has been created with the child list model1Id. Instead of repeating the same process for the second model model2Id, ZtClone is used with the function Arglist containing the ZtRECURSIVE attribute set to TRUE. The call ZtChange() changes the colors.

```
int ret_val;
ZtId model1Id, model2Id;
/*  objectArglist for colors  */
static ZtArgListItem colorArglist [ ] =
{
    ZtBACKGROUND_COLOR,(ZtValueType)red,
    ZtFOREGROUNDCOLOR,(ZtValueType)black,
    NULL,(ZtValueType)NULL
};
/*  functionArglist for recursive attribute  */
static ZtArgListItem recursiveArglist [ ] =
{
    ZtRECURSIVE,(ZtValueType)TRUE,
    NULL,(ZtValueType)NULL
}
                                .
                                .
                                .
                                .
    model2Id  =  ZtClone(model1Id, NULL, recursiveArglist);
    ret_val   =  ZtChange(model2Id,colorArglist,
                 recursiveArglist);
```

Cloning nonrecursively (ZtRECURSIVE = FALSE) can be used in cases where objects need to be referenced but copies of these objects are not needed. Fig. 4 shows the data structure that would result after nonrecursively cloning the objects referenced by the linked list called List1. Instead of copying the objects, a new linked list (List2) of pointers is created for referencing the objects. The original and newly cloned list will dereference the same objects. HP IVIBuild, the builder component of HP IVI, makes use of this option of ZtClone to duplicate lists of selected objects. The cloned lists are manipulated through the use of list functions to provide the undo and backup capabilities of HPIVIBuild (see page 36).

When an object is no longer needed, the function ZtFree can be used to free all memory allocated for the object. Arglists can also be freed using the function ZtFreeArgList. This function will free all memory associated with the Arglist including the additional memory allocated for attributes.

Manipulate Attributes

Most attributes of existing objects can be modified. For example, in an application in which a text object contains a string that indicates elapsed time, the time needs to be updated periodically. ZtChange can be called passing the new value of the elapsed time in the ZtSTRING attribute of the object Arglist.

ZtChange also provides a way to modify several objects in one call. The user simply has to put all the desired objects into a list and issue a ZtChange call on the list object. The changes will be made to all objects that the list references. In the following code fragment the foreground color is changed for all objects referenced by the identifier listId.

```
/*  arglist for foreground color  */
static ZtArgListItem fgcArglist [ ] =
{
    ZtFOREGROUND_COLOR,          (ZtValueType)NULL,
    NULL,                        (ZtValueType)NULL
};
int return_val;
    fgcArglist[0].ZtValue = (ZtValueType) steelblue
  /*  Steelblue is the index into the system object's color list          */
  /*  (the ZtCOLOR_LIST attribute on the ZtSYSTEM_OBJ).                   */
  /*  change the color to steelblue                                       */
    return_val = ZtChange (listId, fgcArglist, NULL);
```

Default values can also be changed with the same call. To change the value of a default attribute, the object type and not the objectId must be sent to ZtChange. For instance, if at some point in the program it is desired to have all the windows have a red background instead of the default blue, a call could be made to ZtChange with the object type set to ZtWINDOW_OBJ instead of the objectId.

Information about the current value of an object's attributes or the default values can be obtained by making use of the ZtQuery call. If required, API will handle the space allocation for the queried values. The following code fragment is requesting information on a pushbutton object.

```
int return_val;
char *querystr;
/*  arglist for querying string                                          */
static ZtArgListItem qstringArglist [ ] =
{
    ZtLABEL_STRING,          (ZtValueType)NULL,
    NULL,                    (ZtValueType)NULL
};
/*  A copy of the pushbuttonId's label string will be returned in querystr */
/*  after the ZtQuery call. A return value of FALSE indicates that       */
/*  memory could not be allocated or an invalid pointer is               */
/*  specified in pushbuttonId.                                           */
      return_val = ZtQuery (pushbuttonId, qstringArglist, NULL);
      querystr = (char*) qstringArglist[0].ZtValue;
/*  the following call frees the memory allocated for ZtLABEL_STRING     */
/*  in the ZtQuery call.                                                 */
      ZtFreeArgList(qstringArglist);
```

Save and Retrieve Objects

The ZtSave function allows users to save objects in a file.

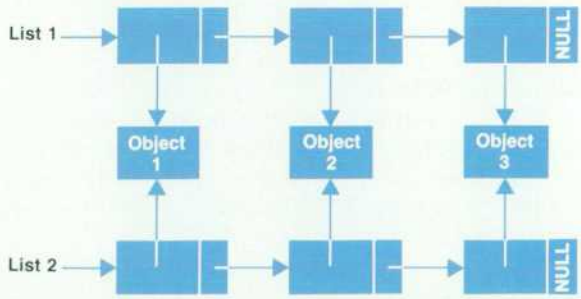

Fig. 4. *Cloning lists of objects nonrecursively.*

A filename can be specified by the user in the function Arglist. If the file exists, the user also has the option to overwrite the existing file. Objects or defaults of one application can be retrieved easily in another application with the ZtRestore call. In the following example the window windowId is saved into a file named windfile.w.

```
int return_val;
ZtId windowId
/*  filename arglist  */
static ZtArgListItem saveArglist[ ] =
{
    ZtFILENAME,        (ZtValueType)"windfile.w",
    ZtOVERWRITE,       (ZtValueType)TRUE,
    NULL,              (ZtValueType)NULL

};

    return_val = ZtSave (windowId, saveArglist)
```

Locate Objects

The capability of locating the closest object near a user-defined point in a window is provided by the function ZtFindByLocation. Users can control the aperture of the search (i.e., how close or how far from the point) and the depth of the search (i.e., whether or not the action should be recursively applied down to primitive objects within any model or composite object). For example, a row-column object contains a pushbutton object, a text object, and a scrollbar object. A mouse click (i.e., a button event) generated on the pushbutton will cause ZtFindByLocation to return the ZtId of the pushbutton if the function Arglist contains the value TRUE for the ZtRECURSIVE attribute. If ZtRECURSIVE is set to FALSE, the return value of ZtFindByLocation will be the ZtId of the row-column object instead of the pushbutton (see Fig. 5).

ZtFindByAttribute also enables the user to match objects that have certain properties. For example, if an application creates a large number of objects and some of them are invisible, to find all the invisible objects, the ZtFindByAttribute function is used on the window object, passing an object Arglist with the ZtVISIBLE attribute set to FALSE.

Receive Input Functions

Input events like button and key presses can be collected using the function ZtDo(ObjectId, ZtINPUT, NULL). Where objectId is the ZtId of a system object and ZtINPUT is the action for ZtDo to do. The input-handling ZtDo function retrieves the events and dispatches them to the appropriate callback function so that the user-defined action can be executed. User input can be collected continuously or in a single pass.

Visual Update Functions

In addition to getting input, ZtDo provides several other actions. It provides the capabilities to update, draw, redraw, flash, erase, raise, and lower objects on the display. The following is a list of the different operations possible with the ZtDo function.

```
/*  redraw all objects whether or not they have been modified      */
ZtDo(systemId, ZtREDRAW, NULL);
/*  draw a window                                                  */
ZtDo(windowId, ZtUPDATE, NULL);
/*  flash an object on the display                                 */
ZtDo(pushbuttonId, ZtFLASH, NULL);
/*  flash the objects on a list                                    */
ZtDo(listId, ZtFLASH, NULL);
/*  erase a rectangle object                                       */
ZtDo(rectangleId, ZtERASE, NULL);
/*  erase a list of objects                                        */
ZtDo(listId, ZtERASE, NULL);
/*  draw a text object whether or not it has been modified         */
ZtDo(textId, ZtDRAW, NULL);
/*  draw a list of objects other than low-level objects            */
ZtDo(listId, ZtDRAW, NULL);
/*  raise a window                                                 */
ZtDo(windowId, ZtRAISE, NULL);
/*  lower a window                                                 */
ZtDo(windowId, ZtLOWER, NULL);
```

Two modes of updating or drawing objects on the display are possible: immediate update and deferred update. In immediate update mode the windows are redrawn anytime there is a visual change in the objects. In the deferred mode, the process of redrawing windows can be postponed until an explicit update is performed through ZtDo(...ZtUPDATE...), or a change in the update mode. This mode is useful if changes need to be made to many objects and it is only necessary to refresh the window once. Both modes are activated by setting the system object's update attribute to either immediate or deferred. The following code puts the system object in the deferred update mode.

```
/*  update mode arglist for system object  */
static ZtArgListItem updateModeArglist [ ] =
{
    ZtDEFER_UPDATE, (ZtValueType)TRUE,
    NULL,           (ZtValueType)NULL
};
ZtId systemId, windowId;
int return_val;
```

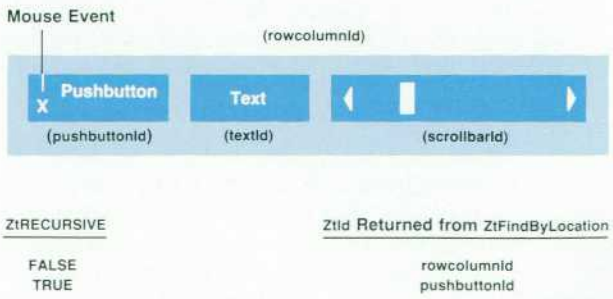

Fig. 5. *Locating an object with* ZtFindByLocation. *When a mouse event happens over the pushbutton, if the* ZtRECURSIVE *attribute is* FALSE *the identifier for the row-column object (*rowcolumnId*) is returned. If the* ZtRECURSIVE *attribute is* TRUE, *the function searches for the primitive object in the area and returns the identifier for the pushbutton (*pushbuttonId*).*

```
/*  at some point in the application, set update mode to deferred  */
    return_val = ZtChange (systemId, updateModeArglist, NULL);
                                .
                                .
                                .
/*  now it is necessary to redraw one of the windows  */
    return_val = ZtDo (windowId, ZtUPDATE, NULL);
```

List Manipulation Functions

The API list manipulation functions allow programmers to create and manipulate lists of objects.

Creating an Object List. The following example creates a list of two points using the function ZtCreateList (see Fig. 6).

```
/*  arglist for point object  */
static REAL64 x, y;
static ZtArgListItem pointArglist[ ] =
{
    ZtX, (ZtValueType)&x,
    ZtY, (ZtValueType)&y,
    NULL, (ZtValueType)NULL
};
/*  Identifiers for pointer objects  */
ZtId point1Id, point2Id, point_list;
/*Identifiers for pointer objects  */
/*  create a point at (50.0,50.0)  */
    x = 50.0, y = 50.0;
    point1Id = ZtCreate (ZtPOINT_OBJ, pointArglist, NULL);
/*  create another point at (60.0,50.0)  */
    x = 60.0;
    point2Id = ZtCreate (ZtPOINT_OBJ, pointArglist, NULL);
/*  create the list for these two points  */
    point_list = ZtCreateList (ZtLIST_OBJ, point1Id, point2Id, NULL);
```

Freeing a List. When the list of objects is no longer needed, it can be freed. The application has the option to free the list along with all the objects it references, or to free the list but retain the objects.

```
/*  free the point list (point_list) in the example above  */
int return_val;
static ZtArgListItem recursiveArglist [ ] =
{
    ZtRECURSIVE,        (ZtValueType)TRUE,
    NULL,               (ZtValueType)NULL
};

/*  free the list and its references, the two point objects  */
    recursiveArglist[0].ZtValue = (ZtValueType)TRUE;
    return_val = ZtFree(point_list, recursiveArglist);

/*  free the list but leave the two point objects alone  */
    recursiveArglist[0].ZtValue = (ZtValueType)FALSE;
    return_val = ZtFree(point_list, recursiveArglist);
```

Bookeeping. Three API functions are provided for retrieving information about list objects. These functions include:

- ZtCheckListObject for verifying the presence or absence of an object in a list.
- ZtCountList for counting the number of objects in a list.
- ZtGetListIndex for determining the position of an object in a list.

Extraction. An object can be extracted from a list of objects by invoking ZtGetListObject and specifying the index of the object, or by using the function ZtGetListTail to extract the last object in a list.

Insertion. Objects can be inserted into a list by using:

- ZtInsertListIndex to place the object at a specified index
- ZtInsertListObject to place the object before an object with a known identifier
- ZtInsertListTail to place the object at the end of a list.

These functions can be used to add an object to the child lists of windows, models, or composite objects. The following code fragments demonstrate using these functions. Figs. 7a and 7b show the results of the ZtInsertListIndex and the ZtInsertListObject examples respectively.

```
/*  insert an object at location two in list pointListId  */
ZtId pointListId, point1Id, newpointListId, insertpointId, refpointId,
     pointId;
int ret;

/*  pointListId : the ZtId of a ZtLIST_OBJ to insert the object into */
/*  point1Id : the ZtId of the object to insert into the list        */
/*  newpointListId: the ZtId of the new list. If the function        */
/*                  fails, the original pointListId is returned      */
/*                  in newpointListId. If the function succeeds,     */
/*                  the new list is returned in newpointListId.      */

    objIndex =2;
    ret = ZtInsertListIndex(pointListId, objIndex, point1Id,
          &newpointListId);
                                .
                                .
                                .
/*  insert an object (insertpointId) into a list (pointListId)   */
/*  in front of another object (refpointId)                      */

    ret = ZtInsertListObject(pointListId, refpointId,
          insertpointId,&newpointListId);
                                .
                                .
                                .
/*  add a point object (pointId) to the end of a point list      */
/*  (pointListId)                                                */

    ret = ZtInsertListTail(pointListId, pointId, &newpointListId);
```

Merging Lists. A list of objects can be merged into another

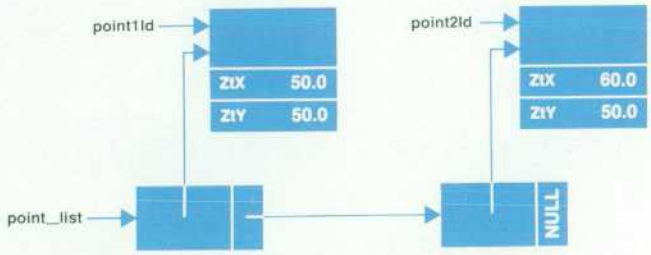

Fig. 6. *Data organization illustrating a list of two points created with the function* ZtCreateList.

list by using:

- ZtMergeListIndex to place the list at a specified index
- ZtMergeListObject to place the list before an object with a known identifier
- ZtMergeListTail to place the list at the end of a list.

In the following example three objects of type ZtLIST_OBJ are used to illustrate merging lists. ListId references three objects (object1Id, object2Id, object3Id), MergeId references two objects (object4Id and object5Id), and NewlistId is the list object obtained by merging ListId and MergeId (see Fig. 8).

```
/*  Using ZtMergeListIndex to insert all objects of MergeId   */
/*  into ListId between object1Id and object2Id   */
    ZtId ListId, MergeId, NewlistId;
    int ret_val;
    INT32 list_index = 1;

      ret_val = ZtMergeListIndex(ListId, list_index, MergeId,
                &NewlistId);
/*  Using ZtMergeListObject to insert all objects of MergeId into   */
/*  ListId in front of object2Id                                    */

    ZtId ListId, MergeId, NewlistId, object2Id; int ret_val;
      ret_val = ZtMergeListObject(ListId, object2Id, MergeId,
                &NewlistId);
```

Removing Lists. Objects can be removed from a list by using:

- ZtRemoveListIndex to remove an object at a specified index
- ZtRemoveListObject to remove an object before an object with a known identifier
- ZtRemoveListTail to remove an object at the end of a list.

Children of windows, models, or composite objects can be deleted by invoking these functions on the list object specified in the ZtCHILD_LIST attribute.

Replacement. An object can replace another object using:

- ZtReplaceListIndex to place the object at a specified index
- ZtReplaceListObject to place the object before an object with a known identifier
- ZtReplaceListTail to place the object at the end of a list.

```
/*  replace a point object at the index position of a point      */
/*  list (pointListId) with a new point object (newpointID)      */

/*  pointListId : the ZtId of a ZtLIST_OBJ to replace the        */
/*                object in                                      */
/*  newpointId : the ZtId of the object to replace the indexed   */
/*               object with                                     */
/*  replacedId : the ZtId of the replaced object. This variable  */
                 may be given as NULL if this return value is
                 not of interest.                                */
```

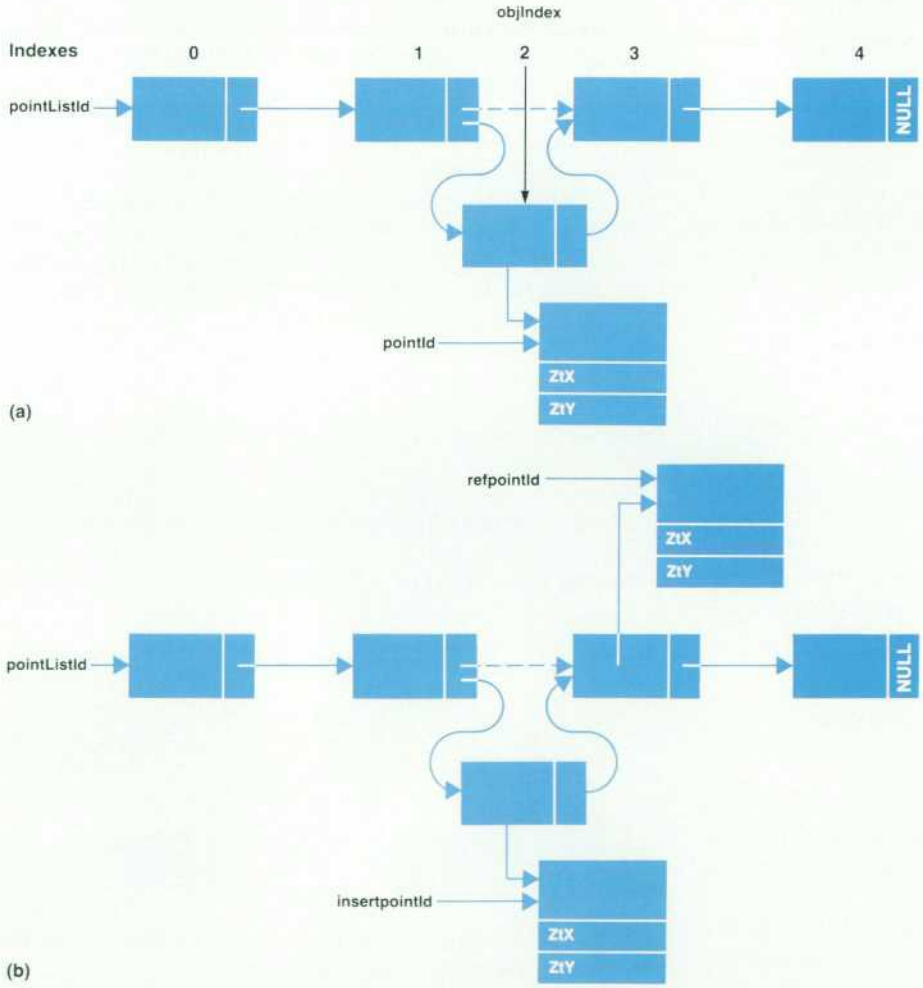

Fig. 7. *(a) Inserting the object* pointId *in the list* pointListId *at index 2. (b) Inserting the object* insertpointId *into the list* pointListId *in front of the object* refpointId.

```
ZtId pointListId, replacedId, newpointId;
INT32 objIndex = 2;
int ret;

    ret = ZtReplaceListIndex(pointListId, objIndex, newpointId,
          &replacedId);

/* The next code fragment illustrates using ZtReplaceListObject */
/* The object identifiers have the following meanings:          */
/* pointListId : same as above                                  */
/* point_index_Id: the ZtId of the object to replace            */
/* newpointId : the ZtId of the object to replace point_index_Id */
/* replacedId : same as above                                   */

    ret = ZtReplaceListObject(pointListId, point_index_Id,
          newpointId, replacedId);

/* replace the tail object of a point list (pointListId)        */
/* with a new point object (newpointId)                         */

    ret = ZtReplaceListTail(pointListId, newpointId, &replacedId);
```

Grouping and Reparenting Objects

Using the methods and techniques described so far, objects can be created and grouped together to form an object hierarchy like the one shown in Fig. 1. This is accomplished using model objects or composite objects. Model objects allow an application to group together composite objects, primitive objects, and other model objects into one group. They are invisible container objects and they do not own any visual attributes. Composite objects have visual attributes and they make it possible to group together primitive widget objects and other composite objects. Examples of composite objects include menus, menu panes, row-columns, and scroll lists. There are two ways of creating model or composite objects in API: creating objects with the child list attribute (ZtCHILD_LIST), or assigning a group of objects to another parent.

Creating Composites with ZtCHILD_LIST

Using ZtCHILD_LIST, model and composite objects and their descendants can be created either top down or bottom up.

Top Down. The composite object is created with NULL assigned to the child list attribute ZtCHILD_LIST. It then becomes the current composite object and all newly created primitive objects will automatically become the composite's children. For example, to create a menu system from the top to the bottom, start from the top of the menu hierarchy and work down creating children. This process is summarized in the following steps:

- Create the menu object ZtMENU_OBJ with the ZtCHILD_LIST attribute set to NULL. This will make the menu the current composite object.
- Create a menu pane object ZtMENUPANE_OBJ. This will make the menu pane a child of the menu object and also make it the current composite object.
- Create the menu button objects. This will make the menu buttons children of the menu pane.
- Change the attribute ZtCURRENT_COMPOSITE on the system object (ZtSYSTEM_OBJ) to the menu object created in the first step. This will make the menu the parent of the next menu pane.
- Repeat the last three steps until all the menu panes and menu buttons are created.

Bottom Up. To create a composite object from the bottom up, create all primitive objects, put them in a list, and then create the composite object setting the ZtCHILD_LIST attribute to the ZtId of the object list. For example, to create a menu system from the bottom up, start from the bottom of the menu object hierarchy, making the newly created objects children of objects higher in the menu hierarchy. This process is summarized in the following steps.

- Create a group of menu buttons and put them in a list object ZtLIST_OBJ.
- Create a menu pane with the ZtCHILD_LIST attribute set to the ZtId of the ZtLIST_OBJ created in the first step.

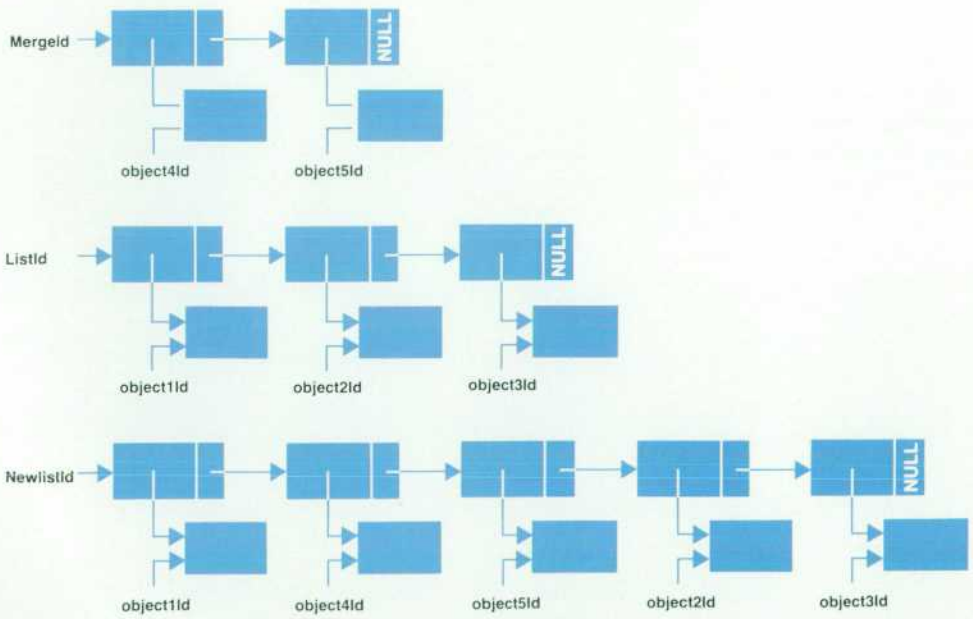

Fig. 8. *Merging lists. The objects on list* MergeId *are merged between the first and second objects of list* ListId *resulting in a new list* NewlistId.

- Repeat the first two steps until all the menu panes and menu buttons are created.
- Put all the menu panes into a list object.
- Create the menu object with the ZtCHILD_LIST attribute set to the newly created ZtLIST_OBJ from the previous step.

Reparenting

In API it is not necessary to destroy all the objects created and start all over when the user wants to change the objects' relationships. Regrouping objects by changing relationships is called reparenting. The ZtChange function makes the task of regrouping very easy. The new child list is simply passed to the desired parent object, and the API takes care of removing the targeted children from the old parent's child list and assigning them to the new parent. For example, the following code segment moves the pushbutton object PushButton 1 from Model 2 to Model 1, and inserts PushButton 1 into the child list of Model 1.

```
ZtId pb1Id;                    /*  PushButton 1 Id   */
ZtId model1Id;                 /*  Model 1 Id   */
ZtId childlist1Id;             /*  Model 1 childlist   */
INT32 ret;                     /*  Return Value   */

static ZtArgListItem childlistArglist [ ] =

{
    ZtCHILD_LIST, (ZtValueType)NULL,
    NULL, (ZtValueType)NULL
};

/*  get the current childlist of Model 1                    */
    ret  =  ZtQuery (model1Id, childlistArglist, NULL);
    if (ret)
    {
        childlist1Id  =  (ZtId) childlistArglist[0].ZtValue;

 /*  add pushbutton pb1Id to the end of the childlist of model 1   */
        ret  =  ZtInsertListTail (childlist1Id, pb1Id,
                &childlist1Id);
        if (ret)

/*  Change model1Id's childlist to include the pushbutton pb1Id   */
/*  The API automatically updates the childlist of model 2        */
            ret  =  ZtChange (model1Id, childlistArglist, NULL);
    }
```

Freeing Model or Composite Objects

The counterpart of cloning model and composite objects recursively or nonrecursively is the ability to free these objects from the intermediate parent. Take the case of an application in which one of its model objects has a row-column object as one of its children. Suppose the application requires that the row-column object be freed, but the children of the row-column object must remain. The API provides an option in the ZtFree function that allows the user to accomplish this task. Setting the ZtRECURSIVE attribute in the function Arglist to FALSE, and calling ZtFree on the row-column object, destroys the row-column object, and its children become the children of the model object. In contrast, passing a function Arglist to ZtFree with ZtRECURSIVE set to TRUE will free the row-column object and its children.

Symbols and Models

Models can be created as children of other models. A model within another model is called a submodel. For example, in Fig. 1, Model 21 is a submodel of Model 12. The user can create a symbol library out of submodels. Customized sets of commonly used symbols can be created, saved, and reused as submodels.

Conclusion

Based on an object-oriented framework, the API consists of a simplified yet powerful set of functions for creating and activating user interface components. The application developer can learn to use these routines within a short time. The developer is also able to combine the dynamic animation capabilities of graphics and the flexibility and interactive capabilities of widgets to enhance user interfaces for process control applications. Models of physical objects such as machinery and instrumentation can be created to provide context-specific information that the end user can react to more quickly than with a standard terminal-oriented interface.

HP IVI Application Program Interface Design

To provide the features available in HP IVI, the internal design and implementation of the application program interface leveraged concepts and software from graphics packages, window technology, widgets, Xt Intrinsics, and object-oriented design.

by Pamela W. Munsch, Warren I. Otsuka, and Gary D. Thomsen

ONE OF THE MAIN goals of the HP Interactive Visual Interface (HP IVI) project was to leverage features from current user interface and software design technologies and blend the best of each into the feature set and design of the application program interface (API) functions. In doing so, the project team investigated windowing, graphics, the X toolkit (Xt Intrinsics), widgets, and object-oriented design. This article discusses the features used from each of these technologies, and how these features are incorporated into the internal design and implementation of the API functions (see Fig. 1).

Windowing

To hide the complexities of the X Window System[1,2] from HP IVI application developers, the API provides a layer of simplifying software over X. The only X features left exposed are those that we thought the application developer must have access to, or that cannot be layered over. Even with this layer of software, the user still has access to X functions. For example, X provides an event called ConfigureNotify that tells the application that a window has been resized, moved, or changed in some way. The API handles resizing the window object when this event occurs but lets the application decide if all the objects in the window should be resized to match the new window's size, or if the objects should maintain their sizes and only the coordinate system of the window should be adjusted. The user still has direct access to the X functions if they are needed.

The API also ensures that all X events (e.g., a mouse button press and release) that occur in a window object are sent to the application. This is done through callback techniques based on the Xt callback mechanism. There are also mechanisms and data structures to provide a linkage between X event data formats and API data formats.

Graphics

Most graphics packages, such as Hewlett-Packard's Starbase graphics package,[3] provide coordinate systems that allow users to write device independent graphics programs. Since creating a user interface with the X Window System is currently done using pixels, the API project team decided to provide API functions that enable user-interface designers the same type of device independent coordinate system features as offered by Starbase.

Graphics packages provide coordinate systems that:

- Communicate with a particular device (device coordinates)
- Provide display resolution independence (normalized or virtual device coordinates)
- Allow the user to work in a system that reflects their world (world coordinates)
- Allow users to move, scale, or rotate images easily without recalculating the placement and size of the image (modeling transformations).

Device coordinates (DCs) are the coordinates used to write to a device. For the X Window System, device coordinates are defined in pixels.

Virtual device or normalized device coordinates (NDCs) provide a means to gain independence from the resolution of the display. This coordinate system maps the width and height of a display to the coordinate range from 0.0 to 1.0. Normalized device coordinates define a viewport. A viewport is a rectangular drawing region on the display surface. Specifying the viewport in NDCs maintains the ratio between the drawing area and the display size regardless of the display resolution.

World coordinates provide a user-defined coordinate system. This system allows users to create pictures using the most appropriate coordinate system for the task. For example, if the world coordinates represent the physical dimensions of a factory, using the dimensions from a blueprint of the factory to create a picture is straightforward. World coordinates define which area of the unbounded

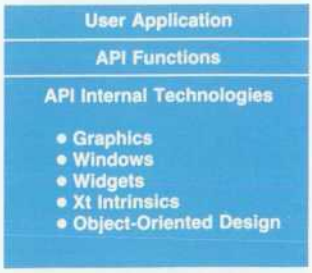

Fig. 1. *The software technologies incorporated into the internal design and implementation of the HP IVI application program interface (API).*

world coordinate space is visible in the viewport. This type of coordinate system also provides viewport-size independence and display-resolution independence since the world coordinates remain the same regardless of the physical size or resolution of the display.

Modeling transformations allow the user to define a slightly different view of the world coordinates for each piece of the picture. Modeling transformations are geometric transformations such as scaling, rotation, and translation (movement). This feature allows the user to draw an object and then reuse it in the picture by moving, scaling, and rotating it to fit the requirements of the picture.

These three coordinate systems and the modeling transformations are linked together when an object is drawn. First, the object is transformed by its modeling transformations to the desired orientation in the world coordinate system. The world coordinates are scaled and translated to fit into the viewport and converted to normalized device coordinates. Finally the normalized device coordinates are converted to device coordinates to draw the picture in the viewport. These transformations are shown in Fig. 2.

Widgets and Xt Intrinsics

The widgets (pushbuttons, scrollbars, etc.) and the Xt Intrinsics provide the basis for the API input model and for other API features. The API project team took the input loop from Xt Intrinsics and added processing to handle API graphics objects. Also leveraged from the Xt Intrinsics are the methods for getting file descriptor input and time-outs. An extension of the Xt callback technique allows users to attach functions to window objects to handle X events and to API graphic objects, which include geometric figures such as circles, arcs, and rectangles, to handle mouse button events.

To keep the number of API functions low, API parameter handling is patterned after Xt Intrinsic Arglists. The API Arglists are arrays of attribute and value pairs. This feature frees the application from having fixed parameter lists that force it to make many calls. The application also doesn't have to pass unnecessary parameters. Parameters that it doesn't pass are automatically defaulted. One deviation from the Xt Intrinsic Arglist is that the API uses a null-terminated list instead of a counted list. The API also extends the attribute default concept so that the application can change the defaults of different classes of objects at run time. API Arglists are described in the article on page 11.

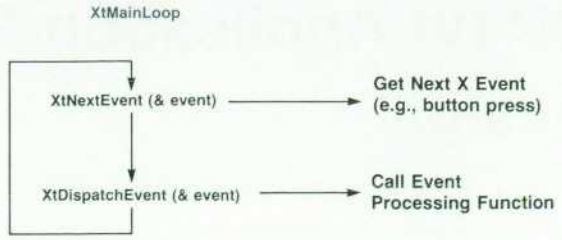

Fig. 3. *The Xt Intrinsics* XtMainLoop *function.*

Object-Oriented Design

HP IVI is an object-oriented system. Object-oriented design and object-oriented programming are being increasingly used at HP for software product development.[4,5] The goals of object-oriented methods are very appealing because they encourage such practices as code reuse and functional cohesion of software components (objects). Also, once a stable and reliable library of objects is available, software development and maintenance costs should be reduced. In the API a special utility was used to create an object-oriented environment from C language programs. The box on page 29 describes some basic object-oriented concepts and an overview of the API object-oriented environment. The special utility used for creating the object-oriented environment is described later in this article.

Input Handling

The input handling model for the API is based on X, Xt Intrinsics, and widgets. The Xt Intrinsics provide a way to call application functions when certain events occur. These functions are called callbacks and are attached to widgets. The Xt Intrinsics provide input handling capabilities for X events, time-outs, and file descriptor input through the XtMainLoop function. This function consists of an infinite loop calling XtNextEvent() to get the next event and XtDispatchEvent() to send the event to the appropriate processing function (see Fig. 3). Because the API provides several spe-

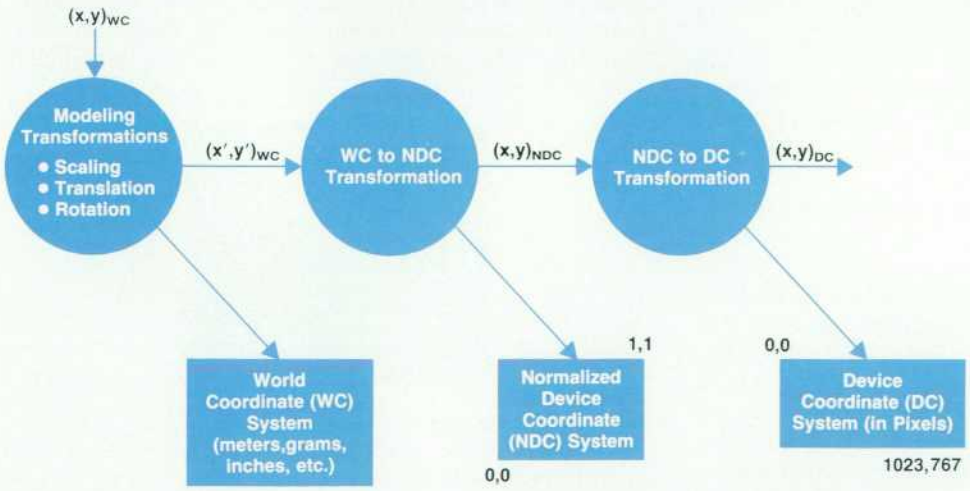

Fig. 2. *The coordinate systems and the transformations involved in transforming an object from world coordinates to device coordinates.*

cial input features the project team implemented its own version of XtMainLoop.

The basic API input loop consists of an HP-UX select() call to see if input exists on either the user's file descriptors or the API server object's file descriptors and a test to see what events came in (see Fig. 4). If input is pending on the file descriptor for the X server a message is sent to the API server object to process all X events queued. If input is pending on a user's file descriptor the user's callback function is invoked.

The server object still does the XtNextEvent() and XtDispatchEvent() looping but it has additional code to handle conversion of X callback information to API format, callbacks on graphic objects and window objects, Expose and ConfigureNotify events on window objects, global callbacks, and event grabbing (see Fig. 5).

Callback Handling

Callbacks are implemented as objects in the API. These objects contain a pointer to the user-written function to be called when an X event occurs, a pointer to callback-specific data, and the specific reason that will cause the callback to invoke the user function (see Fig. 6). The file descriptor that is checked during input processing is an example of callback-specific data. The reason for the invocation of the callback is an integer value that indicates the type of input event such as a button press. These callback objects are put in a list called a callback list and are attached to the object requiring them. For the Xt Intrinsics, the callbacks are attached to specific-reason resources instead of one central callback list. The API method of handling callbacks eliminates having one attribute per callback for each object type and eliminates having to add and delete attributes when reasons change. Time-outs and file descriptor callbacks are attached to the API system object, which stores global attributes and resources. X event callbacks are registered on the window objects.

The API creates an identifier (ZtId) for each object that an application creates. However, the data returned to callbacks from a widget consists of a widget identifier and widget-specific data, which is unusable to API applications. This problem is solved by minifunctions that are registered with the widgets. These minifunctions are interfaces that convert widget-specific data into something that can be understood and used by the API. When a minifunction is attached to a widget, the object identifier ZtId is also attached to the widget. This scheme allows widgets to be treated like other API objects when widget input is received.

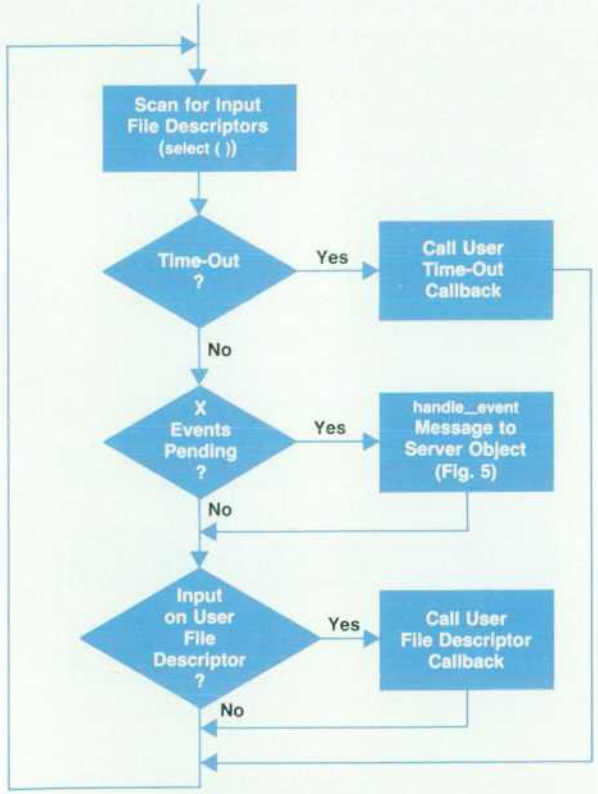

Fig. 4. *The API input loop.*

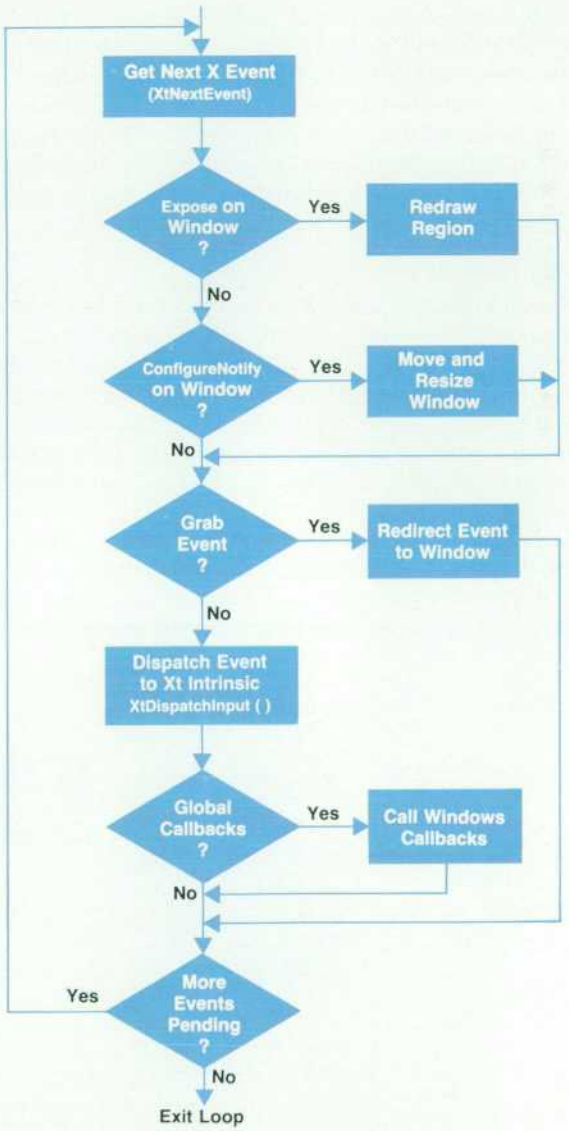

Fig. 5. *The API server object event handling loop.*

Callbacks on Graphics

Graphic objects include shapes such as arcs, rectangles, and circles. Because graphic objects can be manipulated the same as windows and widgets in the HP IVI environment, we decided to have button press and button release events associated with them. Therefore, graphic objects need callback functions. For example, an octagon-shaped graphic object representing a stop sign may require a callback object with a method for stopping some operation. Callbacks on graphic objects are handled differently from widgets. Since the graphic objects are not widgets, the Xt Intrinsics cannot be relied on to call API functions when an event occurs on a graphic object. All widget and graphic objects have a corresponding extent object. The extent object consists of two point objects that define a rectangular region. When associated with an object, the extent defines the smallest rectangle that encloses an object (see Fig. 7). When the minifunction for window events detects a button press or button release, it converts the x,y coordinate position of the sprite to a point object. Since the window minifunction is called, this indicates that the button event did not occur over a widget (remember the widget minifunction converts widget data to API usable data). The button event results in a call to a function to find the object that is under the point. The function will search the hierarchy for an object that has the point in its extent. If a graphic object is found, the object list is searched to see if there is a corresponding callback function and if so, the event is dispatched to the function.

Global Callbacks

A requirement of the API was to detect a function key press regardless of the location of the sprite in the window. This was a problem if the sprite was over a widget when a function key was pressed because widgets grab any input over them. The project team extended the callback process so that the window object could also receive the event even if it was over a widget. This type of callback is referred to as a global callback.

Global callbacks are implemented by providing an additional check during the input processing in the server object (see Fig. 5). After the event is dispatched to the appropriate object, a check is made to see if global callbacks are enabled. If so, the event is dispatched again to the window object and any global callbacks attached to the window that match the event are called. For events that were originally over widgets, the x,y coordinates of the event are recalculated to be relative to the API window object before dispatching. Recalculation of widget points is done because the API understands points relative to the window object coordinate system and not to the widget coordinate system.

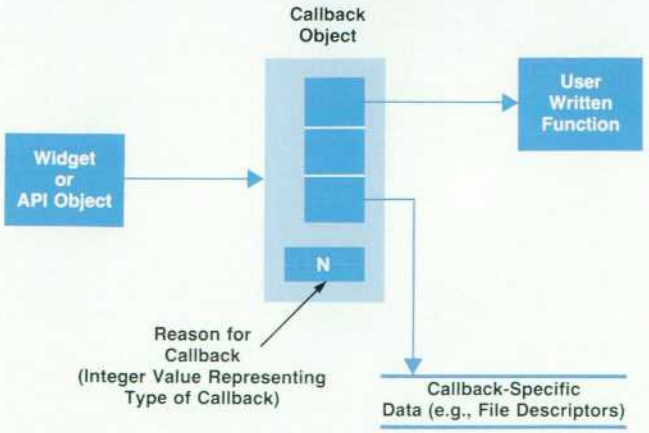

Fig. 6. *A callback object in the API.*

Event Grabbing

For customers making their own user-interface builders and also for HP IVIBuild, a feature was needed to direct events only to the window. For example, the normal behavior for a widget pushbutton object is to flash when it is selected. However, in the builder, selecting the pushbutton may be the start of a move operation on it. To suppress normal widget behavior and let the application determine the meaning of the event, a button press event over a widget has to be directed only to the window object. The event has to be grabbed. To solve this problem, input handling at the server object level was modified so that if event grabbing is enabled, the event is only sent to the window object for processing.

Window Expose and Resize

When Expose and ConfigureNotify events occur on API window or graphics objects, special functions are called in the server object to handle these events. Since graphic objects are not in individual X windows as the widgets are (see Fig. 8), the window object has to redraw the graphic objects when an Expose event occurs and resize its children when a ConfigureNotify event occurs.

For an Expose event, the window object removes all Expose events for this window from the queue and keeps two lists of corresponding extent objects. Remember that an extent object consists of two point objects that define a rectangular

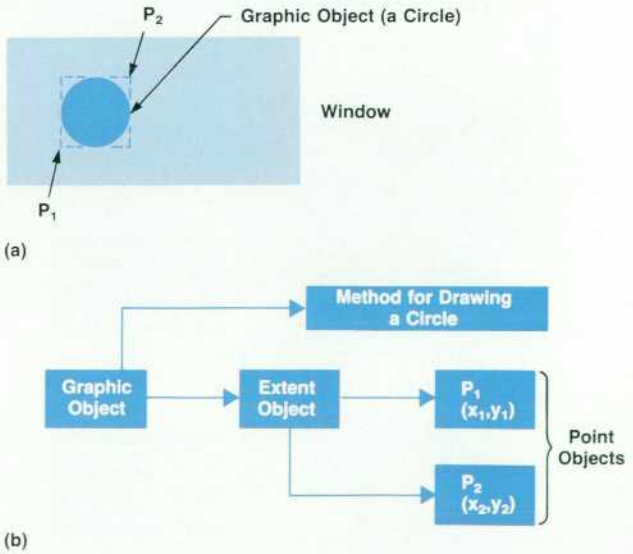

Fig. 7. *An API graphic object with an extent for defining the smallest rectangle around a graphic object. (a) The graphic object (a circle) in a window and the extent represented by P_1 and P_2. (b) internal representation of the graphic object.*

region. One list contains the extents of each Expose event in device coordinates. This list is used in the server object to create X clip rectangles when graphics objects in the exposed region are redrawn. The second list contains extents of each expose event in normalized device coordinates. After constructing these two lists, the window object goes through a redraw pass of the objects in the window. When the graphics objects are told to display themselves, they check the previous normalized device coordinate clip list to see if they are in the exposed areas. If they are, they send a message to the server object to do the X drawing commands. This scheme ensures that only those objects that are actually exposed get redrawn by the server object and it significantly improves performance if exposed objects are only a small portion of the window.

For ConfigureNotify events, the window object sets the new window placement and size values. Then during the next redraw of the window, the objects are redrawn to fit within the new window size.

Coordinate Systems

The coordinate system concepts and techniques found in various graphics packages are incorporated into the API functions for drawing graphics objects, windows, and widgets on the display. The user can define the viewing area in world coordinates (e.g., inches, feet, etc.) and the API functions transform these coordinates to a window in the X coordinate system pixels.

A viewport is a rectangular portion of the display onto which window objects defined in world coordinates are mapped. Viewports are typically defined in a device independent coordinate system called normalized device coordinates, or NDCs. In X a viewport is represented by an X window, which is defined in device coordinates (DCs). The API allows users to define the position and size of a window object (viewport) with NDC coordinates. This allows a window to be defined as occupying a certain portion of the total display area independent of display resolution. Mapping a window object described in NDCs to the device coordinates of a display is straightforward. When an application initiates drawing to a specific X server, the display resolution of the server is queried. The NDC values describing the viewport are multiplied by this display resolution to get pixel values. Since NDCs use the lower-left corner of the display as the origin and X uses the upper-left corner as the origin, the y values of the viewport must be subtracted from the height of the display for compatibility with the X coordinate system. Since this calculation is done at run time, the application does not need to know the type of display the application is using.

Consider a window that occupies the NDC region from (0.0,0.0) to (0.5,0.5) on a display that is 1024 pixels wide and 768 pixels high (see Fig. 9a). When converted to DCs as explained above, the window occupies the region of the display at pixel locations (0,767) to (511,384) (see Fig 9b).

The transformation equations for converting from NDCs to DCs are:

$$P_{xDC} = P_{xNDC} \times (\text{width of display in DCs/1 NDC}) \quad (1)$$

$$P_{yDC} = P_{yNDC} \times (\text{height of display in DCs/1 NDC}). \quad (2)$$

To take into consideration the upper-left origin of the X Window System:

$$P'_{yDC} = \text{height of display in DCs} - P_{yDC}. \quad (3)$$

Substituting the values from Fig. 9a into equations 1 and 3 and compensating for the starting pixel yields:

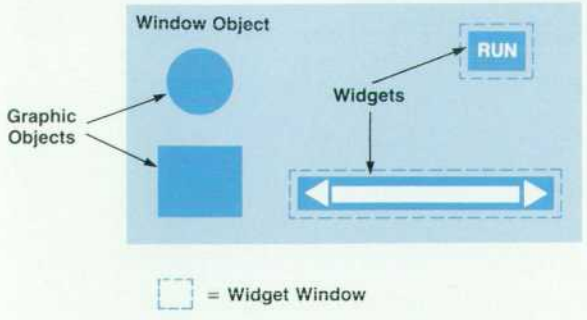

Fig. 8. *Widgets are in their own individual windows and have their coordinates defined relative to these individual windows. Graphic objects have their coordinates defined relative to the window object they are located in.*

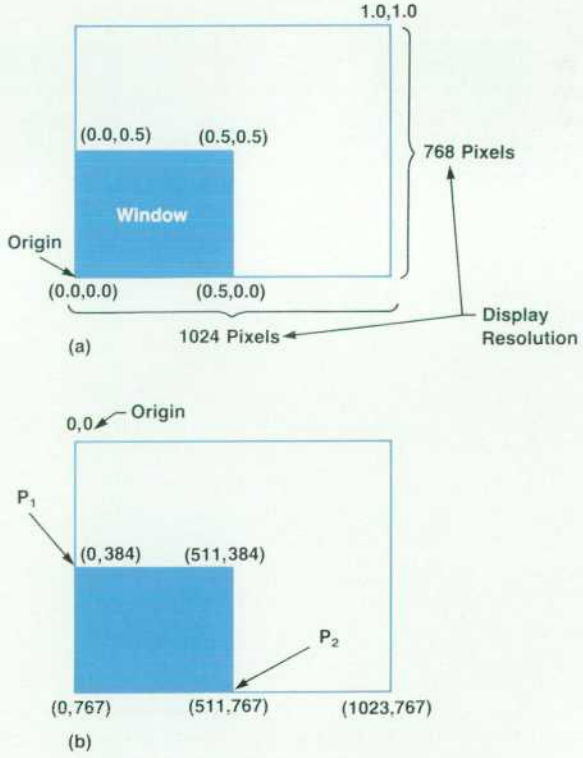

Fig. 9. *(a) Window defined in normalized device coordinates (NDCs). (b) The same window defined in device coordinates (DCs) in the X Window System.*

$P_{1xDC} = 0.0 \times 1024/1 = 0$
$P'_{1yDC} = 768 - (0.5 \times 768/1) = 384$
$P_{2xDC} = (0.5 \times 1024/1) - 1 = 511$
$P'_{2yDC} = 768 - (0.0 \times 768/1) - 1 = 767.$

These coordinate values are shown in Fig. 9b.

To define what is drawn within the window object, the user defines what portion of the world coordinate (WC) space is viewable in that area. This viewable area can be changed at run time to perform operations such as panning or zooming. To draw to the X window representing the user's window object, the API must convert all values in WCs into the device coordinates of the display. WCs are transformed to pixels in a two-step process. The first step transforms the WCs to NDCs and the second step transforms the NDCs to DCs.

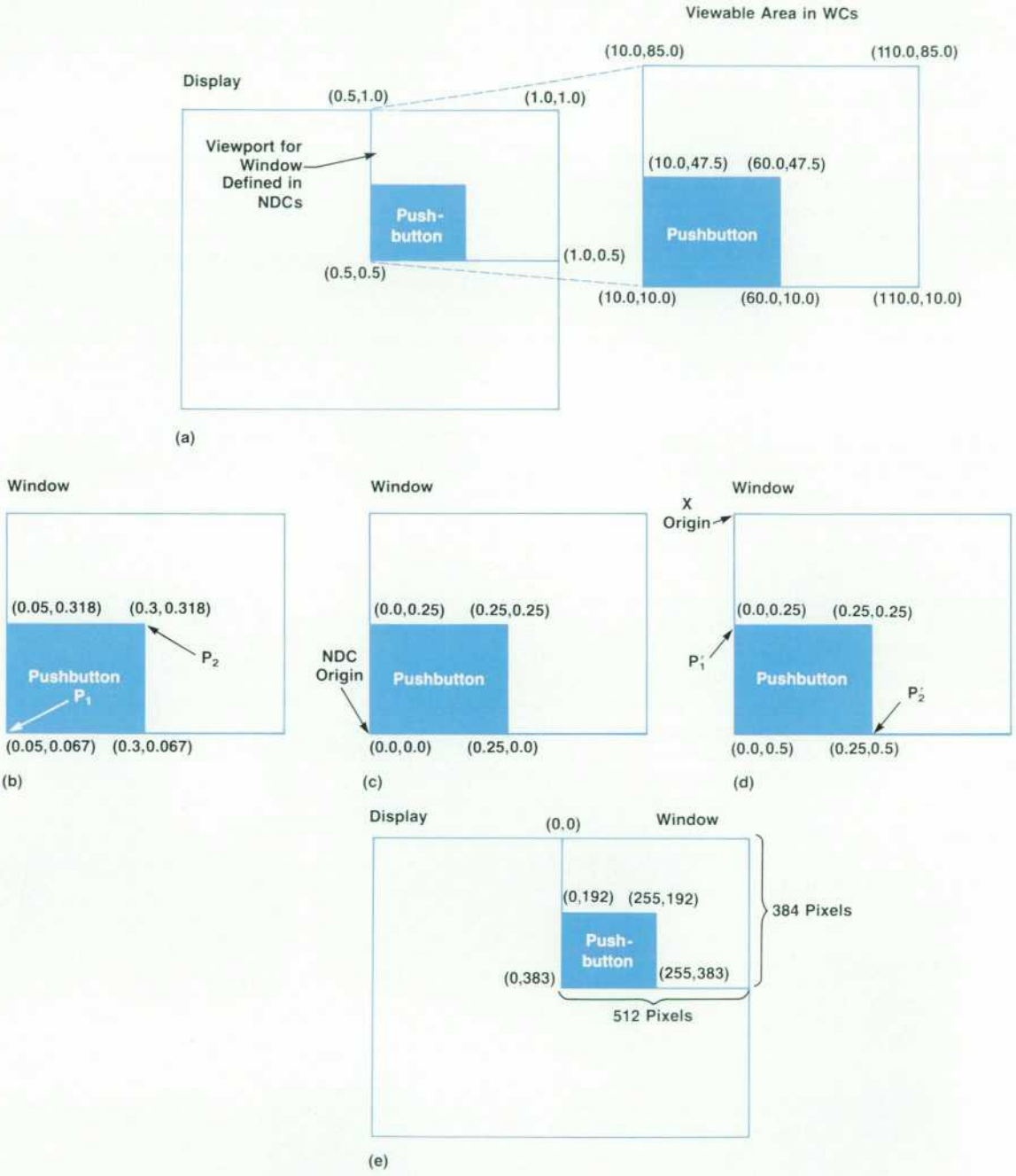

Fig. 10. *(a) The viewable area of the world coordinate window is defined to occupy the upper-right quadrant of the display. (b) Results of applying the x and y scale factors to the pushbutton coordinates. (c) Results of applying translation factors to the scaled pushbutton coordinates. (d) Results after applying the flip factor to compensate for the X window origin in the upper-left corner of the NDC space. (e) Results after transforming the pushbutton from NDCs to DCs.*

Every window object contains a viewport-to-window transformation matrix (**VTM**). This matrix describes how to scale and translate the viewable WC region to fit within the window. A scale factor (SF) is calculated to scale the WC width and height to the width and height of the viewport. This scale factor for the x coordinate is:

SF_x = width of the window in NDCs ÷ width of the viewable WC region in WCs

and for the y coordinate is

SF_y = height of the window in NDCs ÷ height of the viewable WC region in WCs.

For example, in Fig. 10a the viewable area of the world coordinate window is defined to occupy a viewport in the upper-right quadrant of a display. The scale factors for mapping the WC region to NDCs in this example are:

$$SF_x = (1 - 0.5)/(110 - 10) = 0.005 \text{ NDCs/WC}$$

and for the y coordinate

$$SF_y = (1 - 0.5)/(85 - 10) = 0.0067 \text{ NDCs/WC}$$

To transform the pushbutton coordinates shown in Fig. 10a from WCs to NDCs:

$$P_{1x} = 10 \times SF_x = 0.05 \text{ NDCs}$$
$$P_{2x} = 60 \times SF_x = 0.3 \text{ NDCs}$$

$$P_{1y} = 10 \times SF_y = 0.067 \text{ NDCs}$$
$$P_{2y} = 47.5 \times SFy = 0.318 \text{ NDCs.}$$

Fig. 10b shows the pushbutton scaled to NDC coordinates.

The NDC system maps the coordinate (0.0,0.0) to the lower-left corner of a window. Therefore, if the viewable WC region does not map the coordinate (0.0,0.0) to the lower-left corner of the window, a translation factor is added to the NDC coordinates. The translation factors are computed as:

$$T_x = -SF_x \times (WC_x \text{ origin})$$
$$T_y = -SF_y \times (WC_y \text{ origin})$$

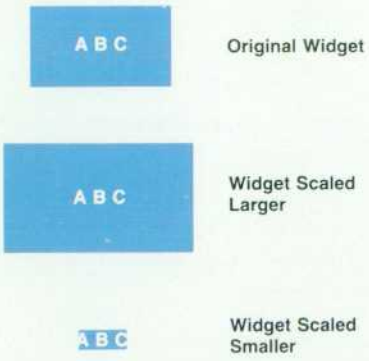

Fig. 11. *The effects of scaling widgets larger and smaller around characters.*

For the pushbutton example the translation factors are:

$$T_x = -0.005 \times 10 = -0.05 \text{ NDCs}$$
$$T_y = -0.0067 \times 10 = -0.067 \text{ NDCs.}$$

Adding the translation factor to the NDC points P_1 and P_2 results in:

$$P_{1x} = 0.05 - 0.05 = 0 \text{ NDCs}$$
$$P_{2x} = 0.3 - 0.05 = 0.25 \text{ NDCs}$$

$$P_{1y} = 0.067 - 0.067 = 0 \text{ NDCs}$$
$$P_{2y} = 0.318 - 0.067 = 0.25 \text{ NDCs.}$$

Fig. 10c shows the results of the translation.

Like most graphics packages, the API follows the convention of defining the origin in the lower-left corner of the drawing area. However, because the X Window System defines the origin to be the upper-left corner, an additional translation factor (or flip factor) must be added in the y direction to move the origin from the lower-left to the upper-left corner.

The NDC height for the window in which the pushbutton in Fig. 10 resides is 0.5 NDCs. Compensating for the flip factor (F) results in:

$$P'_{1y} = F - P_{2y} = 0.5 - 0.25 = 0.25 \text{ NDCs}$$
$$P'_{2y} = F - P_{1y} = 0.5 - 0.0 = 0.5 \text{ NDCs}$$

and

$$P'_{1x} = 0.0$$
$$P'_{2x} = 0.25.$$

Fig. 10d shows the result of applying the flip factor.

The scale factors, the translation factors, and the flip factor are incorporated into the viewport-to-window transformation matrix **VTM**. Combining all the transformation factors in one matrix and performing the transformation operations looks like:

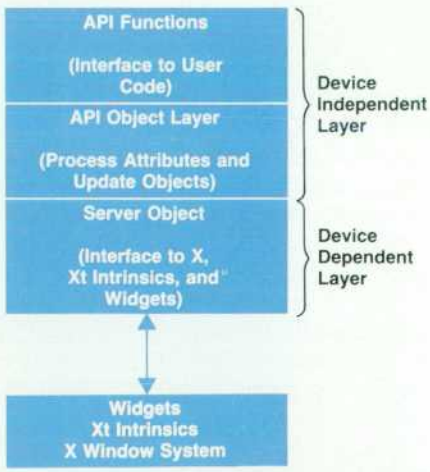

Fig. 12. *The layers of the API architecture.*

$$[P_{xNDC}\ P_{yNDC}\ 1] = [P_{xWC}\ P_{yWC}\ 1]\begin{bmatrix} SF_x & 0 & 0 \\ 0 & -SF_y & 0 \\ T_x & (-T_y + F) & 1 \end{bmatrix}$$

Fig. 10e shows the final transformation of the pushbutton NDCs to X window device coordinates. The coordinate points shown in Fig. 10e are derived by substituting the values from Fig. 10d into transformation equations 1 and 2 and compensating for the starting pixel.

$$P_{1xDC} = 0.0 \times 1024/1 = 0$$
$$P_{1yDC} = 0.25 \times 768/1 = 192$$
$$P_{2xDC} = (0.25 \times 1024/1) - 1 = 255$$
$$P_{2yDC} = (0.5 \times 768/1) - 1 = 383.$$

Modeling Coordinates

The API provides modeling transformations that allow any object within the user interface hierarchy to be transformed by scaling (enlarging or shrinking), rotation, and translation. This lets the user draw a symbol that can be reused by providing only the data that differentiates its position and size from another instance of the symbol. The API concatenates modeling transformations so that an object is affected by the transformations on its ancestors. This allows an entire subhierarchy of objects to be transformed by one operation on a common ancestor instead of requiring transformations on every object in the subhierarchy. These transformations are used when an object is being drawn. The modeling transformation values are converted to WCs by multiplying the transformation on an object to its WC attributes. A current transformation matrix (**CTM**) is maintained during a drawing pass on the objects. Each object multiplies its transformation matrix with the **CTM** containing the transformations of its ancestors. In the API, the **CTM** is initialized to be the **VTM**. Doing this reduces the number of matrix multiplications and improves the performance of the drawing operation.

Adjustments and Scaling

Besides allowing the application developer to work in a display resolution independent manner when creating the windows for an application, the world coordinate system allows a user to resize the window interactively and the objects to be redrawn without the intervention of the application. Changing the size of the window changes the NDC definition of the window. This change causes the scaling factors in the **VTM** to be recalculated at the next display pass. The objects are either enlarged or shrunk to fit within the new window size. When resizing a window, the user may change its aspect ratio. That is, the physical width-to-height ratio of the object may be different from the WC width-to-height ratio. When this happens, objects begin to look distorted. For instance, a circle begins to look like an oval. This may be an appropriate action for some applications, but for others, especially those where the objects on the display are meant to represent something in the physical world, the application developer wants the objects to maintain their width-to-height ratio. In graphics packages, these two modes of operation are referred to as anisotropic and isotropic scaling, respectively. The API window object provides the attribute ZtADJUST which the application can set to ensure that the aspect ratio is maintained. If this attribute is set and the window is resized, the WC height or width mapping to the window is adjusted to maintain the original aspect ratio. This process results in modifying the scale factors stored in the **VTM**. This also results in more viewable WC space in the window in either the x or the y direction.

Applying the various coordinate systems to windows and widgets has worked successfully. Specifying their position and size in NDC or WC units allows the user to define them in the same manner as graphic objects. It also allows the application to be independent of the display and window size even as the user interactively resizes the window.

Scaling and moving widgets works the same as for graphics objects. However, as the widgets scale smaller and larger, the font that they use does not scale because it is a bit-mapped font. The widget scales larger and leaves more space between the edge of the text and the edge of the widget or it scales smaller and closes in on the text, eventually clipping it (see Fig. 11). A few possible solutions to this problem exist. One solution is for the X Window System to support scalable fonts. This will allow the font to scale with the widget. Another solution is to switch between a set of fonts with different sizes as the object grows and shrinks. Widgets also cannot rotate from a horizontal base. In the API, when a widget is rotated, its defining point is rotated, and the widget is redrawn in the new position with a horizontal base. This allows the widgets to be rotated as part of a symbol and to move along with any associated graphic objects. Despite these differences

(continued on page 30)

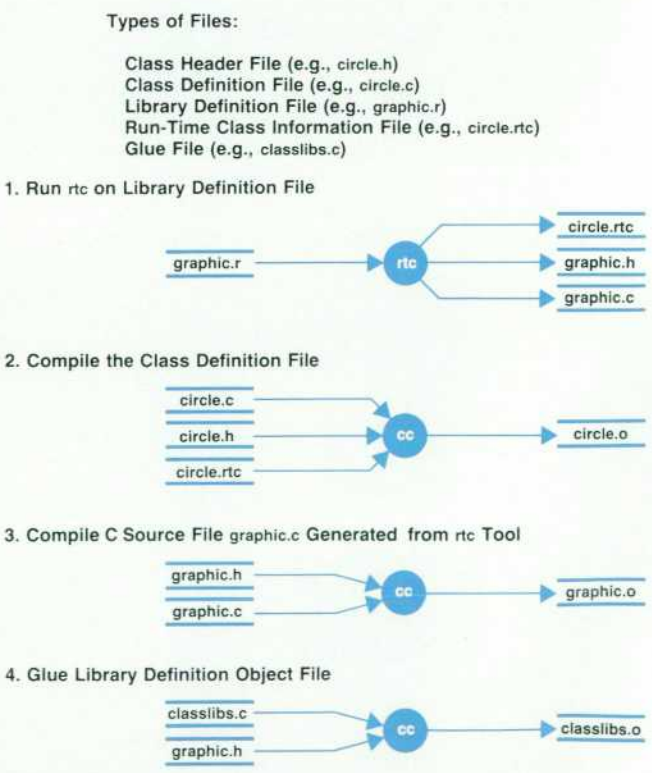

Fig. 13. *The process of adding a new object to the API object hierarchy.*

Object-Oriented Design in HP IVI

HP IVI is an object-oriented system. It uses a set of facilities called the HP IVI object-oriented environment (OOE) to provide the framework for its implementation. The OOE has two parts: a messaging interface and a tool for compiling an external description of the class hierarchy into C language code. The C code defines the dispatch tables used by the OOE's interface functions to perform messaging (object communication). Presented here are some basic concepts of object-oriented design and an overview of how the OOE implements some of these concepts.

Object-oriented design and programming are proving to be a natural and productive paradigm for software development because they enable developers to represent relationships among system components and the tasks to be performed on these components in a more natural manner. The main concepts of this methodology include objects, messaging, polymorphism, and inheritance.

Objects. An object is the basic unit in object-oriented methodology. It is a structure that contains local data structures and references to local procedures (called *methods*) that operate on the data (see Fig. 1). The current values of an object's internal data define the object's current state. The object's behavior is dependent on its current state. The data inside an object is private and accessible only through one of the methods associated with the object. An object acts on its data when it receives a request asking one of its methods to perform some operation. This mechanism is called messaging.

Objects are created from a template called a *class*. There can be many objects of each class. These objects are called instances of the class. Each instance is an independent object with its own data and state. However, an object instance has the same data structures, shares the same methods, and behaves the same way as all other instances of the same class. This means that objects of the same class will respond to the same messages—differences in object behavior depend on the current state (the values of the object instance's data). For example, all object instances of an object class that draws rectangles will respond in the same way to a request to draw a rectangle. However, because of differences in the state of the internal data structures, the rectangles may be drawn in different sizes, colors, and positions.

The OOE tool mentioned above is called the rtc (run-time class information) tool. The rtc tool compiles a symbolic external representation of the class hierarchy into the data necessary for defining classes and methods for those classes. The symbolic representation of the class hierarchy is compiled by the rtc tool to produce static tables called *dispatch tables* which consist of two pieces: a category table and method tables. These tables contain information necessary to dispatch messages to objects. A unique key called the *message selector* is used to search the dispatch tables for a pointer to a function that will service a request. The rtc tool also generates a file containing definitions of symbolic names for the constants that represent the message selectors. Coding using the symbolic names for the message selectors provides independence from the structure of the underlying dispatch tables and provides more readable code. The rtc tool and the type of files it compiles and generates are described in more detail on page 31.

Messaging. Objects communicate with each other through messaging. Sending a message to an object requests that object to perform some action—usually the manipulation of its internal data. Messages consist of a minimum of two arguments: the receiver of the message (i.e., the object) and the message selector. The message selector consists of a category name and a method name. The object receiving the message looks up the category selector in the category table and then looks up the method in the corresponding method table. This selection mechanism is controlled by a set of central messaging routines. These routines are contained in the message interface to the OOE. Every object contributes a dispatch table that the messaging routines search to determine which object implements a function for a particular selector. Associated with each selector is a pointer to a method that is called to implement the response to the message (see Fig. 2).

This connection of a message selector to the appropriate method is called *binding*. Binding can take place at compile time (early or static binding), or at run time (late or dynamic binding). The OOE currently implements static binding.

In the OOE, the message selector is the key to determining which function gets called when a message is sent to a particular object. The message selector is a 32-bit quantity consisting of

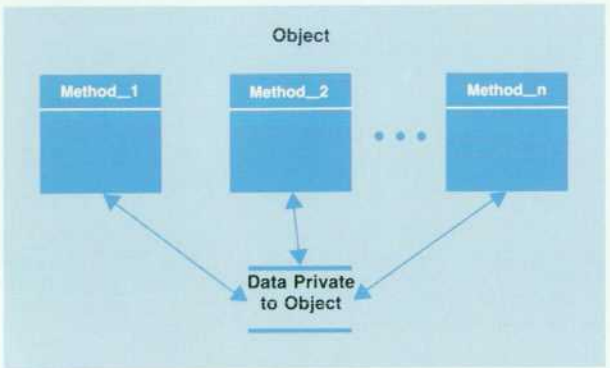

Fig. 1. *An object. The internal data structure is private to the object and the methods have sole access to the data.*

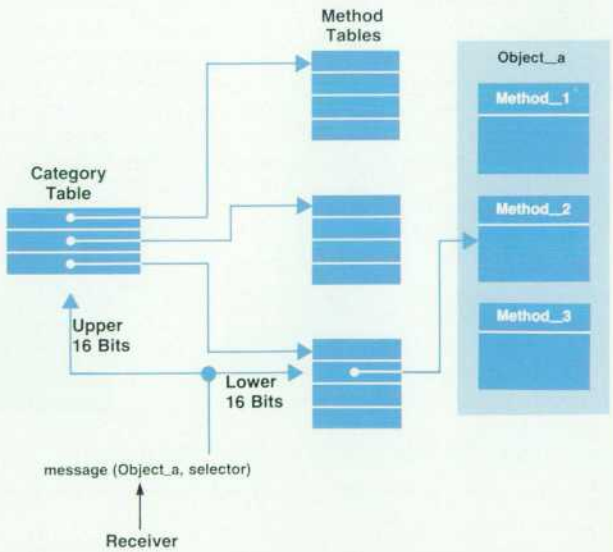

Fig. 2. *Connecting a message to a method in an object.*

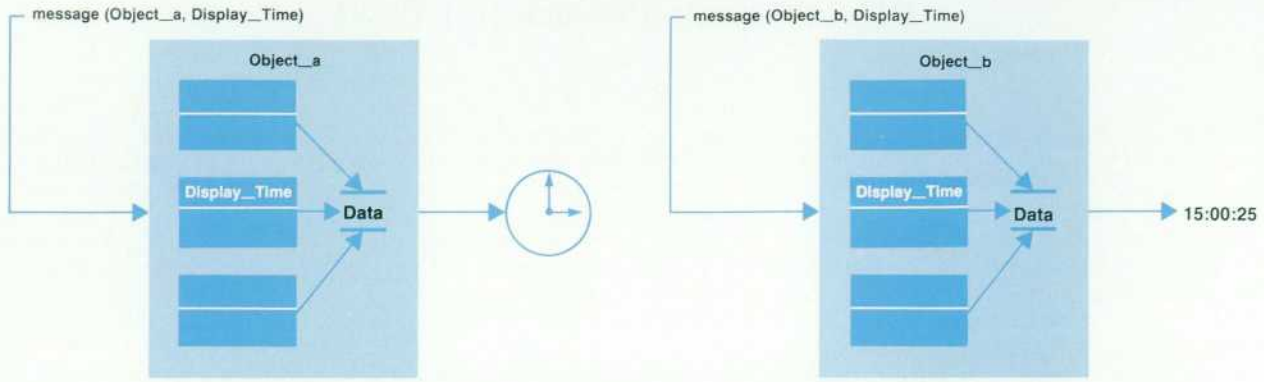

Fig. 3. *Polymorphism allows the same message to be sent to different objects regardless of their internal data types and methods.*

two 16-bit fields. The upper 16 bits of the selector defines the offset of the category to which that message belongs in the class's category table. The lower 16 bits defines the offset of the method function pointer in the method table.

If the value of a particular position in the dispatch table is NULL, the messaging routines traverse up the class hierarchy searching for a method function pointer. When a function pointer is found, it is copied to the position in the dispatch tables where the upward traversal of the class hierarchy began. This tends to improve the performance of the messaging system over time because the amount of upward searching is slowly replaced by direct function calls and the NULL values in the dispatch tables gradually disappear. Also, the implementation of categories improves memory use by eliminating method tables when a class does not support that category.

Polymorphism. The concept of polymorphism in object-oriented programming enables different types of objects to share a common operational interface and to be manipulated by user code independent of the actual types of objects. This means that the application program does not have to differentiate the object type at run time. This differentiation is performed automatically by the messaging system. For example, a message to a clock object to display the time would redraw the hands in a particular position if the clock were drawn as an analog clock, while the same message would cause the time to be displayed in text format for a clock drawn as a digital clock (see Fig. 3). The clock object is polymorphic because the same message can be sent to different objects. The application does not have to worry about how the time is drawn. That is determined when the method to draw the clock interprets the instance data that defines each clock object's internal state. A goal of object-oriented design is to maximize code generality, flexibility, and reusability by defining common interfaces that can be supported by many different kinds of objects.

The mechanism of searching the class hierarchy described above is how the OOE implements the concept of polymorphism.

Inheritance. Inheritance provides the ability to create incremental definitions of objects (i.e., one kind of object can be defined incrementally in terms of previously defined objects). The new definition extends the existing definitions by adding data to the object representation, by adding new methods, and by extending the definition of existing methods. Using the update time example from above, the analog clock object that produces the graphic representation of the time might only implement the method that draws the representation of the clock and inherit the more basic functions (e.g., audible alarms) from the more general digital clock class. Inheritance allows object definitions to be shared (rather than copied) and customized by extension (rather than by modification). A goal of object-oriented design is to organize object definitions so that common behavior is specified in shared definitions and object definitions can be extended.

The external representation of the class hierarchy that is processed by the OOE class compiler (rtc tool) builds tables of function pointers. Entries that are not NULL in these tables indicate that a particular class implements a particular method. NULL entries indicate that a particular class inherits a particular method. The class compiler also declares a pointer to the class's parent in the hierarchy (see Fig. 4). The OOE messaging routines use this information to traverse upward in the class hierarchy when searching for a method.

In object-oriented systems, classes may have one parent or many. Single inheritance allows a class to have only one parent. This is the model implemented by the OOE. Object-oriented languages such as Smalltalk and C++ allow classes to have more than one parent. This is called multiple inheritance.

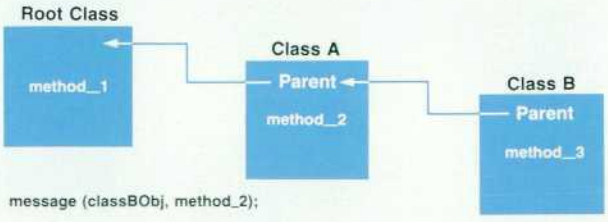

Fig. 4. *Inheritance allows methods to be reused.*

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between the operation of the widgets and the graphic and window objects, the coordinate system feature of the API still provides a large productivity gain for the application developer.

Object-Oriented Architecture

Without using an object-oriented programming language, the API encompasses features provided by an object-oriented language through conventional C language features. The API's architecture is divided into three layers: the API function layer, the API object layer, and the device dependent layer (see Fig. 12). The API function layer provides the communication interface between a user application and the objects created by the application. It is a thin layer of code that validates the user's parameters and sends messages to the objects to perform the tasks requested. The functions provided in this layer are described in the article on page 11. In the API object layer, an object is created and destroyed and all manipulation of an object's data occurs. In the device dependent layer, all the function calls to underlying subsystems are made to draw an object to the display.

Messaging in the API

The API consists of a number of function calls that provide the communication path between an application and the underlying objects manipulated by the application. Most of the API functions require objects as parameters. It is through this interface that an object's specific data and the functions that manipulate the data are accessed. In essence, the API hides from the user as much as possible the details of using objects.

To provide the interface between an application and its objects, a preprocessor tool called rtc (run time class information) is used to define the API object messaging facility and class interitance hierarchy based on information from a group of description files. Every API class consists of a class header file and a class definition file. The class header file defines the data storage for each instance of an object of that class. This file identifies the object as a member of a class or classes and provides the connection to the set of methods that manipulate that object's internal data. The class definition file is a C program module that contains the methods that are specific to a particular class. The class header file must be included in the C program module so that the data structure of this object and the class definition pointer can be accessed. Once an object's data structure, class, and specific functions are defined, it needs to be positioned within the class hierarchy. The positioning of the class in the class hierarchy is determined by the nature of the class and the methods to be inherited. The simpler a class is, the higher up in the class hierarchy it is positioned. Conversely, a more complex class is positioned further down in the class hierarchy. The positioning of a class within the class hierarchy is defined within the library definition file. This file defines the methods that are available for messaging to a class and the methods that can be inherited by that class.

Adding an API Object

Adding a new class to the API class hierarchy is a four-step process. This process is illustrated for the circle class in Fig. 13. First, the library definition file (graphic.r) is used as the input to the rtc tool. The rtc tool takes the library definition file and produces several files as output. One of these output files (circle.rtc in Fig. 13) is the run-time class information file, or .rtc file. A .rtc file is created for every class defined in the library definition file. It contains the class definition structure and the method dispatch tables for that specific class. The .rtc file is included at the end of the class definition file for that class when the class definition file is compiled (step 2). In the third step the new library definition files (graphic.h and graphic.c) are compiled. Finally, the pointer to the new class must be added to the file that defines the class hierarchy. This file is called the glue file (classlibs.c). In step four, classlibs.c is compiled with the class header file (graphic.h) to produce the object file classlibs.o.) When these object files (circle.o, graphic.o, and classlibs.o) are linked into an application, the addresses to the methods supported by the various classes are resolved.

By using object-oriented technologies, the API is able to create graphic objects. One problem users have with software systems such as the X library is that graphic primitives are not objects. The X library provides many graphic functions that operate on the individual pixels of a graphic display but the parameters describing the object are not kept. For example, if a circle is drawn and the application simply wants to change its color from blue to red, all the parameters (location, size, line width, etc.) to draw the circle must be passed to the X library function again. The API solves this problem by providing graphic objects using the rtc tool. This allows the user to describe the parameters of the object once and then make simple modifications only to the parameters that are changing. The application is freed from maintaining all of the data necessary to redraw all of the graphical objects in the window.

Conclusion

The HP IVI project was successful in blending graphics, windowing, X toolkit, widget, and object-oriented technologies in the internal design of the API. Because most of these technologies were developed separately, it was not always clear how to integrate them. The API solved most of the problems encountered and as a result of this effort a high-level user interface toolkit was created that reduces the complexity of building a sophisticated graphical user interface for an application.

Acknowledgments

Besides the three authors, the other members of the API development team were Scott Anderson, Hai-Wen Bienz, Mark Thompson, and Mydung Tran.

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HP IVIBuild: Interactive User Interface Builder for HP IVI

Using the facilities provided by HP IVI's application program interface, HP IVIBuild allows developers to create and experiment with different types of application user interfaces, save them in files, and bind them to the functionality of the application at run time.

by Steven P. Witten and Hai-Wen L. Bienz

THE EDITOR/BUILDER COMPONENT of the HP Interactive Visual Interface product is HP IVIBuild. As its name implies, HP IVIBuild is a tool that is used to build user interfaces interactively. The windows and objects that make up the user interface can be saved in a file and reused later by other applications using the API functions (see Fig. 1). HP IVIBuild is itself an HP IVI application program because it uses the API functions described on page 11 as a platform. Fig. 2 shows the architecture of HPIVIBuild.

Early in the design of HP IVIBuild we realized that although the HPIVI application program interface (API) functions are several orders of magnitude easier to use than Xlib, the X toolkit, and widgets, they are still very complex to many users. Therefore, an interactive user interface design tool, HP IVIBuild, was developed to complement the API functions.

HP IVIBuild helps promote software development productivity in areas such as rapid prototyping and the design and modification of user interfaces. For rapid prototyping, HP IVIBuild allows developers to create complex prototype user interfaces. The user can interactively place and size all of the primitive graphics and widget objects in a window. Once the objects are placed and sized, many of their physical attributes such as colors, shadows, strings, and fonts can be changed easily within HP IVIBuild. Even someone who does not have any software background, such as a human factors expert, can use HP IVIBuild to design a

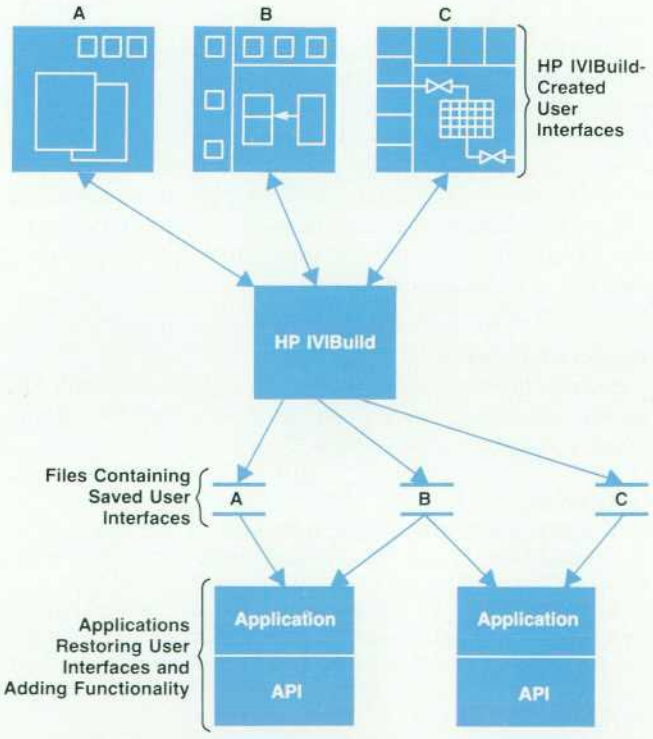

Fig. 1. *HP IVIBuild allows users to create and experiment with different user interfaces and save them in files to be reused by other API applications. (API = application program interface of HP IVI.)*

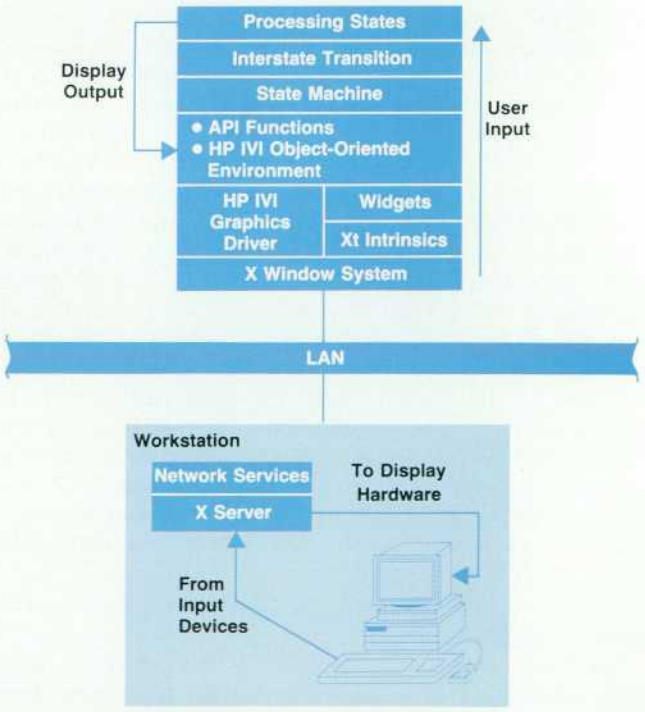

Fig. 2. *The components that make up the HP IVIBuild architecture.*

complex user interface. This means that an application's user interface can be prototyped and evaluated separately from the operations performed in the application.

Besides restoring the user interfaces created with HP IVIBuild, the API functions in the application also make the objects in the interface react to user input. Callback functions, which are invoked in response to user input to the application, can be attached to those objects that should respond to user input. If the application requires changes to the user interface in response to application or customer needs, the previously saved user interface can be modified with HP IVIBuild. If the changes involve adding new objects, callbacks can be added to the new objects using the API functions in the application program. However, if changes are made to existing objects, no changes need to be made to the application program.

Fig. 3 shows the interface areas provided by HP IVIBuild. The functions of these areas are:

- Utility Box. This area displays current object information and the menus for object manipulation.
- Tool Box. This is the area in which the user selects the objects to be manipulated.
- Workspace. This area displays the windows being created.

Object-Oriented Design in HP IVIBuild

HP IVIBuild uses the API functions and the facilities provided by the HP IVI object-oriented environment to build its own object-oriented system. The object-oriented concepts of objects, polymorphism, and inheritance are incorporated into the design of HP IVIBuild.

Objects. In HP IVIBuild objects are very simple data structures called states. A state is the context of user input (i.e., the operation in progress) at any particular point in time. All states are static (bound at compile time) and have the same structure. Only one field in the structure, called a message selector, is filled in at run time. This field is used to bind HP IVIBuild's user interface presentation to its functionality. User interface binding and functionality are discussed later in this article. The following is the C language structure of a typical state object.

```
CLASSVARS(ClassVars)                /* This macro is included for          */
                                    /* compatibility with the HP IVI       */
                                    /* object-oriented environment and     */
                                    /* is not used by HP IVIBuild.         */

extern struct ClassDef _DzRect;     /* Structure containing pointers to    */
                                    /* this state's method dispatch        */
                                    /* tables. This structure is           */
                                    /* created by the API rtc tool.        */

static INT32 groupmembership [ ] { /* Array containing a state's           */
   =NULL                            /* group membership information.       */
};                                  /* The purpose of this array is to     */
                                    /* help limit state transitions        */
                                    /* at certain times. Currently         */
                                    /* this feature is not used in         */
                                    /* HP IVIBuild.                        */
```

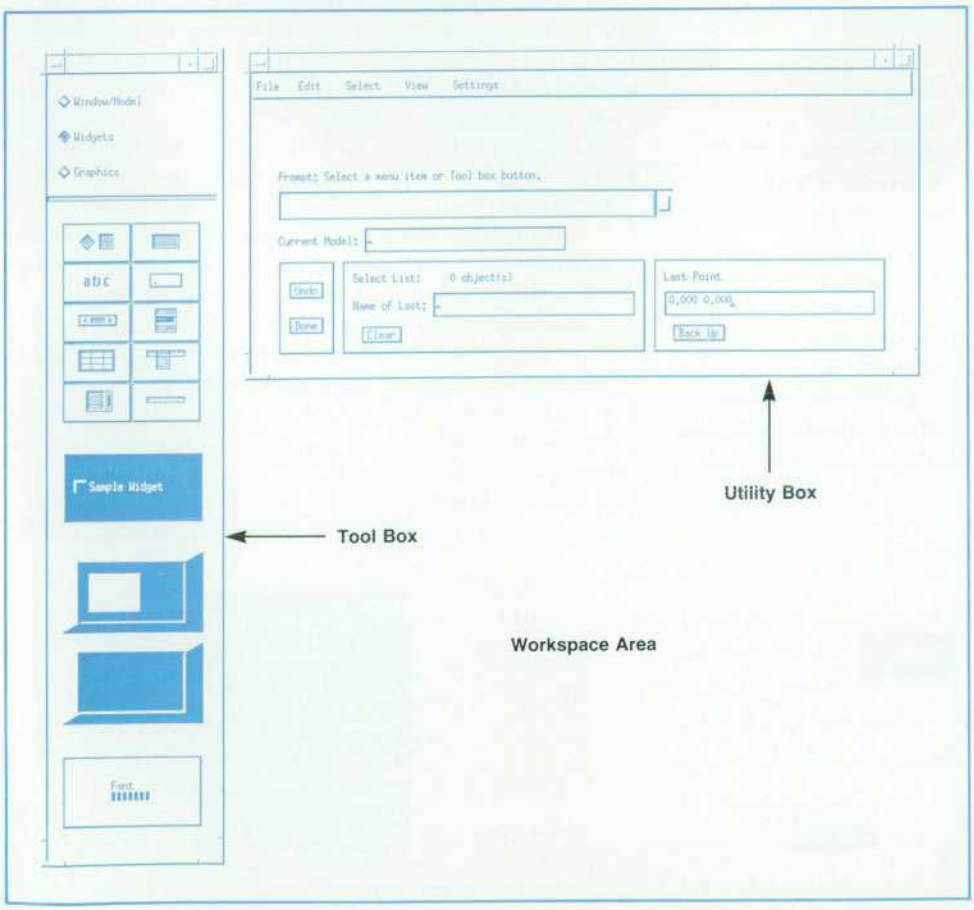

Fig. 3. *Interface areas of HP IVIBuild.*

```
static char objectname[ ] = "s_rect"; /* this state's name */

/* All state objects have the following structure. */

static struct DzRect {
        struct ClassDef *class;      /* Pointer to the dispatch tables.      */
        char *statename;             /* Pointer to the state's name.         */
        INT32 clsindex;              /* A unique id assigned to this state.  */
        INT8 autoterm;               /* This state's autotermination         */
                                     /* flag (if TRUE the state machine      */
                                     /* terminates the state and if FALSE    */
                                     /* an action by the user must           */
                                     /* terminate the state).                */
        INT32 selector;              /* Message sent to the current state    */
                                     /* to cause a transition to this        */
                                     /* state.                               */
INT32 *group;                        /* Pointer to this state's group        */
                                     /* membership information.              */
}

/* Data values assigned to the fields defined above                          */

_state_rect = {                      /* Initialization.                      */
        &_DzRect,                    /* Pointer to dispatch tables.          */
        objectname,                  /* Pointer to name.                     */
        27,                          /* State's id number.                   */
        FALSE,                       /* State is NOT autoterminating.        */
        _s_rect,                     /* Message selector that causes         */
                                     /* transition to this state.            */
groupmembership                      /* Pointer to group membership          */
                                     /* information.                         */
};

idState s_rect = (idState)&_state_rect; /* A pointer to this state           */
                                       /* that is used by HP IVIBuild       */
                                       /* to access and manipulate          */
                                       /* data in this structure.           */
```

Inheritance. In HP IVIBuild, as in most object-oriented systems, state objects are arranged in a hierarchy. At the root of the hierarchy is a special state known as the root state (see Fig. 4). The root state in HP IVIBuild manages interstate transitions. Since the root state is at the top of the object hierarchy, it implements many more methods than the other states in HP IVIBuild. Using inheritance, the lower-level objects inherit all the methods from the root state. This inheritance mechanism is used to implement state transitions in HP IVIBuild.

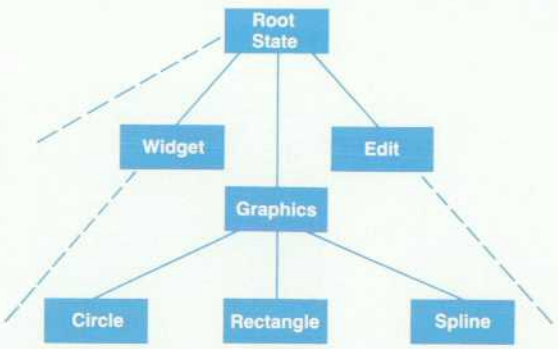

Fig. 4. *A portion of the HP IVIBuild object hierarchy.*

Polymorphism. HP IVIBuild's central input handling facility, which is called the *state machine*, depends on the concept of polymorphism. All states in HP IVIBuild have the same operational interface (i.e., the state object is polymorphic). Therefore to the state machine, all states look the same and are able to respond to the same set of messages. The state machine does not know or care which state is currently active. It only knows that the current state either implements or inherits all the methods that are the targets of messages being sent to it.

The box on page 29 provides a brief review of object-oriented concepts and the HP IVI object-oriented environment.

Input Handling

Messages sent by the state machine to a particular state can result in either an interstate transition or an intrastate transition depending on the message that is sent. Interstate transitions are transitions among the various state objects of HP IVIBuild, and intrastate transitions are transitions within a particular state object.

A new state becomes current by an interstate transition. Interstate transitions are handled by the state machine. All input in HP IVIBuild goes through the state machine. The state machine is an API callback function that is attached to all the components of HP IVIBuild's user interface and all of the workspace windows created by the user. The objects in the HP IVIBuild user interface are called *user-interface objects*, and the objects created by the user during an HP IVIBuild session are called *user-workspace* objects. Using this mechanism, HP IVIBuild is able to control the context of the user's input. This is an important requirement of any interactive design tool.

The state machine performs the following functions:

- It changes the active workspace windows when the user requests it.
- It interprets the meanings (context) of the mouse buttons when they are pressed in the active workspace window according to a user-definable mouse button map.
- It sends messages to the current state.
- It manages the state stack. The state stack is an array of message selectors for the state objects.
- It makes new states current and terminates others that have completed.

The Current State

There is always a state that is active. This state is called

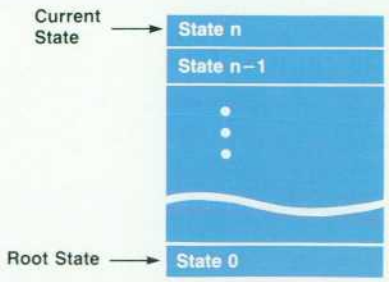

Fig. 5. *The state stack.*

the current state. The current state is always the state to which the state machine sends any messages. It is up to the current state to provide a target method for any messages that the state machine may send it. The target method is located either by implementation or by inheritance. If no operation is in progress (i.e., only one state on the stack), the current state is the root state. If an operation is in progress, the current state is the state that implements that operation (e.g., creation of an object such as a polyline or widget).

No state knows which state was current before it became current and no state knows which state will become current after it ceases being current. These rules were strictly enforced to ensure the black-box nature of each state's methods during design and testing.

Once current, a state controls the context of the user's input according to a state transition mechanism of its own. These state transition mechanisms are called intrastate transitions and are controlled entirely by the state itself using a local variable called a *substate*. For example, moving forward or backward in a sequence of actions that are part of one particular operation, such as creating a polyline, is controlled entirely by the state itself. The substate mechanism is described later in this article.

State Stack Management

During the execution of HP IVIBuild the states that are activated by the user are organized in a LIFO (last-in, first-out) stack (see Fig. 5). The state machine provides a mechanism to suspend operations in progress to do another operation and then resume the suspended operation when the new operation finishes. The state at the top of the stack represents the current context of the user's input and is the current state. Only the current state can receive any messages. The maximum depth of the state stack is defined to be ten states. This is an adequate depth because there are other mechanisms in HP IVIBuild that prevent the state stack from growing to a depth of more than three or four states. The root state enters the state stack first and remains there during the entire execution of HP IVIBuild. Therefore, the root state is always in the stack regardless of the depth of the stack.

At each interstate transition, the state machine checks the autotermination flags of each state in the state stack. If the autotermination flag is TRUE, that state is terminated immediately by the state machine and removed from the state stack. The state stack is then compacted and the state ending up at the top of the stack is started. If the autotermination flag is FALSE, only an action by the user can terminate the state.

State Transition and Inheritance

As mentioned earlier, an interstate transition is the process of making a new state (a state not currently on the state stack) the current state. The new state is placed at the top of the state stack and started by the state machine. The state transition process begins when an event occurs such as a button release over an object on the display. The first thing to happen is that the state machine function is called as part of the normal API callback processing (see page 23). The state machine function is passed a pointer to the ZtUSER_DATA attribute of the object that received the event, which has a pointer to the message selector that, when sent to the current state, will cause an interstate transition to a new state. The state machine sends the message to the current state. This process works the same way for HP IVIBuild user-interface objects and user-workspace objects, except that user-workspace objects always send a hit message to the current state. A window created by the user is the only user-workspace object that functions like a user-interface object. A hit message results when a user presses a mouse button in a workspace window.

If the current state can handle the message, the method that is called will either return a pointer to the current state or a NULL. This pointer is returned to the state machine as part of the normal message sending mechanism of the HP IVI object-oriented environment. States return pointers to themselves when they want to remain current. This will cause an intrastate transition. States return NULL when they receive an exit message and want to cease being the current state. This will cause an interstate transition. Fig. 6 shows a portion of the state transition process.

Since the root state is the parent of all other states, the interstate transition process depends heavily on inheritance. Each state inherits all the methods from the root state. When a state receives a message for which it does not have a method, the HP IVI object-oriented environment will search the current state's lineage (object hierarchy) until it finds the target method for the message. In the case of an interstate transition, the target method will always be found in the root state. The target method in the root state returns a pointer via the object-oriented environment's messaging system to the state object that is to be made the current state. This is the pointer that the state machine compares to the value of the pointer for the current state. When it sees that the two pointers are different, it

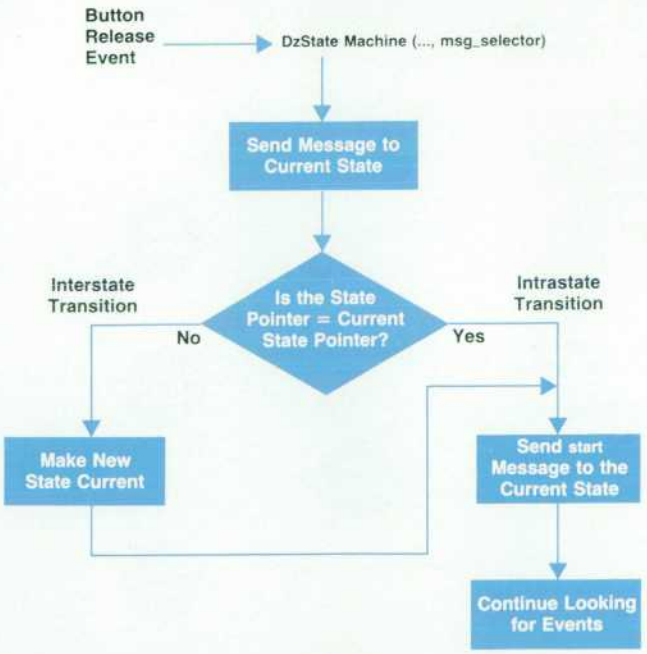

Fig. 6. *The state transition process.*

places the new pointer at the top of the state stack (making the state current) and sends a start message to the new state. Thus, by inheritance, every state object has the ability to activate any other state object.

When an intrastate transition occurs, there is no change to the current state (i.e., the pointers are equal). The current state handles the incoming message itself.

State Protocol

All states follow a specific protocol that is implemented in the state machine of HP IVIBuild. Fig. 7 illustrates this protocol. An interstate transition (Fig. 7a) occurs when the current state receives an exit message and it returns a NULL to the state machine indicating that it wants to cease being the current state. The state machine makes the new state the current state and sends a start message to the new state. The new state remains the current state as long as it continues to return a pointer to itself to the state machine (e.g., Current_State in Fig. 7b). Following this protocol allows a state to control the meaning of user input within its own context. Each state implements or inherits five standard methods that constitute its operational interface: start, hit, backup, undo, and exit.

Start. As shown in Fig. 7, the start message is the first message a state receives before any other message is sent to the state (except exit).

Hit. A state gets a hit message when the user presses a mouse button in the workspace window that is currently active. HP IVIBuild allows the user to construct and edit as many windows as desired but only one can be active at a time. To activate another window, the user only has to press a mouse button over the window that is to become active. Depending on their hit methods, states are classified as either multiaction or single-action states.

A multiaction state requires the user to select multiple points in the active window to perform the operation implemented by the state. An example of a multiaction state is one that allows the user to create polylines or splines. When the user presses a mouse button in the active window and a multiaction state is the current state, the action of the state is said to go forward. Fig. 8 shows the intrastate transition diagram for a multiaction state that translates objects.

A single-action state does not require a hit in the active window to go forward. Single-action states can only do one thing. An example of this are selections (i.e., states that select certain kinds of objects for further operations). Once the class of objects that are to be selected is known, the objects are selected and no further input from the user is required. Any single-action state that receives a hit message is terminated and removed from the state stack. The hit message is sent to the the new current state. Fig. 9 shows the intrastate transition diagram for all single-action states.

Backup. All multiaction states implement backup. This is the reverse operation of a hit message because it allows the user to cause the action of the state to go backward over a previously sent hit. No single-action states implement backup.

Undo. All states implement undo. Undo allows the user to back a state up to the point right after it received its first start. This has the effect of undoing any actions that had been performed by the state. Undo may also be sent immediately after a previous undo to effect a redo operation.

Exit. A state is sent an exit immediately before its removal from the state stack. This allows the state to reinitialize

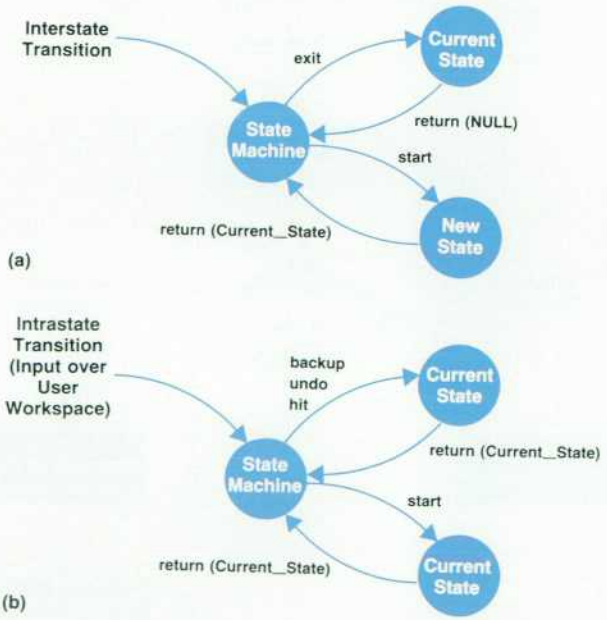

Fig. 7. *HP IVIBuild state protocol. (a) An interstate transition. (b) Intrastate transition.*

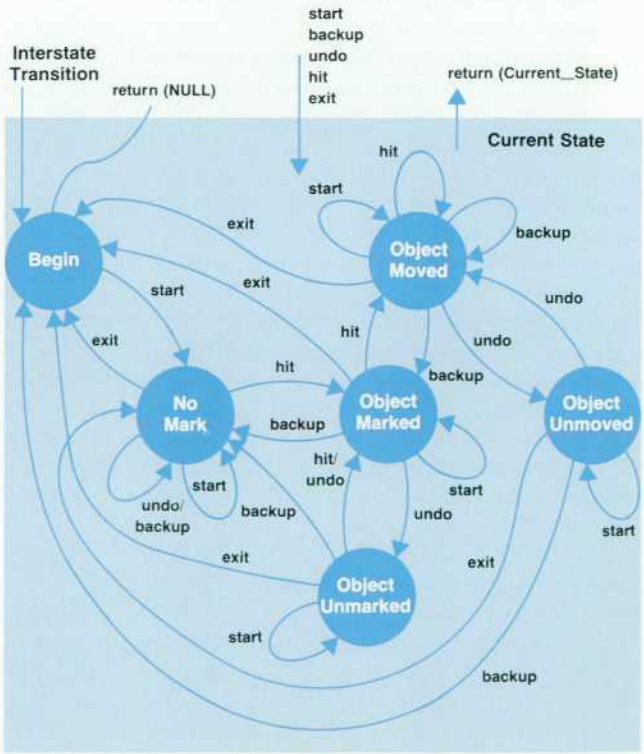

Fig. 8. *Intrastate transition diagram for a multiaction state that translates objects. These states are substates of the current state shown in Fig. 7b.*

itself for its next activation.

The Substate

Once current, a state controls its own actions using a local variable called the substate. During a sequence of operations, the messages start, backup, hit, and undo may be sent repeatedly to the current state. These actions do not cause interstate transitions. Rather, they cause intrastate transitions. The current state does not change but the meaning of the next input event may have to be interpreted differently depending on the sequence of messages the state has received since it was made current. The value of the substate is changed to reflect the context of the next hit, backup, or undo. Note that start is always sent after every action whether the action causes an intrastate or interstate transition. This is part of the protocol established for a state by the state machine.

Uniformity

Great care was taken to ensure that the same actions have uniform behavior no matter which state is current. The HP IVIBuild team developed guidelines for developing states, and intrastate transition diagrams were developed before the development of a particular state so that the uniformity of actions could be assessed by the whole team. The result is a tool with very modular units of functionality that all behave in a consistent and intuitive manner.

The HP IVIBuild User Interface

HP IVIBuild's user interface was designed as a collaborative effort between the HP IVIBuild team members and the industrial design department at HP Software Engineering Systems Division (see the article on page 39). The objective of the collaboration was to design a user interface for HP IVIBuild that was both attractive and intuitive to the user.

Besides the appearance, HP IVIBuild is structured to handle native language support and user customization. One other interesting feature is that the HP IVIBuild user interface presentation is not bound to the functionality until run time.

Native Language Support and Customization

HP IVIBuild's user interface conforms to HP standards regarding support for native languages and cultures. All text that is presented to the user such as labels, prompts, and error messages is contained in message catalogs and is retrieved by HP IVIBuild at run time. To localize HP IVIBuild, the user only needs to change the contents of the catalogs. In general, these tasks are performed by HP personnel in the country whose native language is the target language. This way, text can be presented with as much context sensitivity as possible. Idiomatic nuances of text presentation are not lost (as they sometimes are with straight translations).

Another feature of HP IVIBuild's user interface presentation is that colors, tiles, fonts, mouse button bindings and icons can be customized for individual users by modifying the X Window System configuration file .Xdefaults. This mechanism allows individual users to customize the presentation of IVIBuild's user interface to suit their own needs (e.g., left-handedness, black-and-white display).

Presentation and Functionality Binding

The presentation of the components that make up the user interface of HP IVIBuild (i.e., the buttons, menus, windows, etc.) and the functionality (the states) associated with these components are bound together at run time. The functionality of HP IVIBuild, that is, the result of pressing a certain sequence of buttons, is not dependent on the user interface presentation. For example, in one user interface presentation, drawing a rectangle might be accomplished by selecting buttons labeled P1 and P2 for the lower-left and upper-right corners of a rectangle and typing the coordinates into a pop-up dialog box. In another user interface,

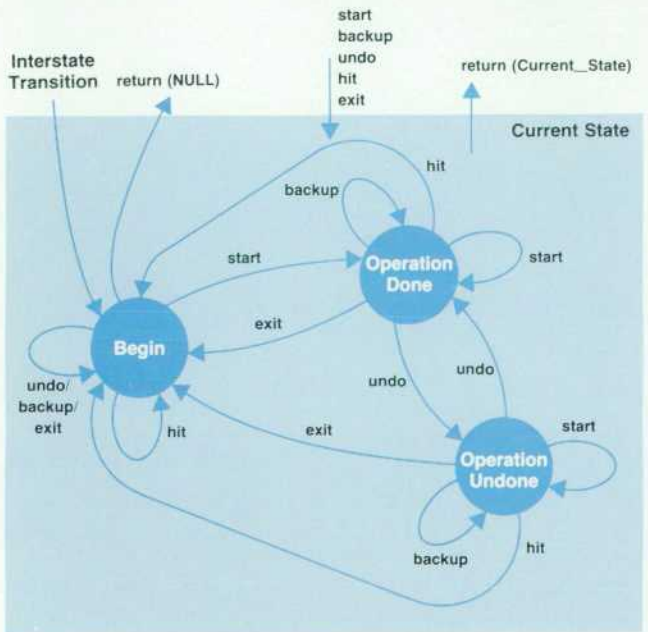

Fig. 9. *Intrastate transition diagram for single-action states. These states are substates of the current state shown in Fig. 7b.*

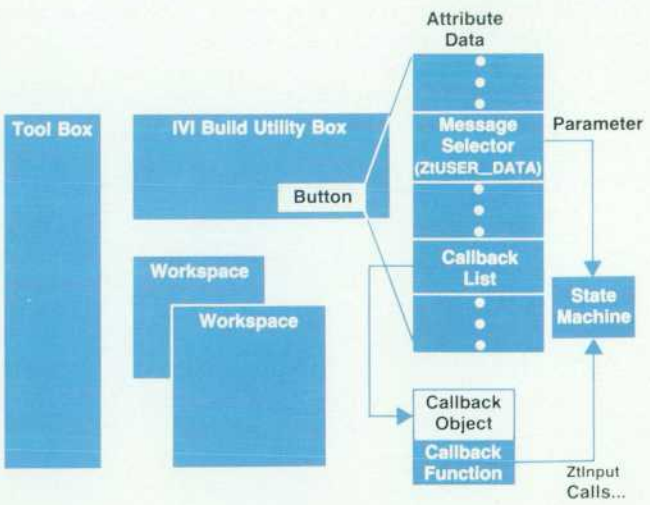

Fig. 10. *Binding HP IVIBuild user interface presentation to functionality at run time.*

drawing a rectangle might be a three-button sequence in which the user presses the Rectangle button and then clicks on the desired coordinates with the mouse. In either interface, the state operations result in a rectangle.

The binding of functionality to user interface presentation is done when HP IVIBuild starts up. At this time the objects (windows, menus, buttons, etc.) that make up the HP IVIBuild user interface are restored from a file. Pointers to objects (ZtIds) that activate states or send messages to the state machine are looked up using the name of the object that was assigned when the object was created with the API functions. This lookup is accomplished using an API function. When the ZtId for an object is returned, the message selector for the state to be activated is retrieved. At this point a callback object (ZtCALLBACK_OBJ), which will call the state machine whenever an event occurs on the user interface object, is created for the user interface object. Also, the message selector from the state object is made an attribute (ZtUSER_DATA) of the user interface object. Once the callback object is attached to the user interface object, the binding is complete (see Fig. 10). When a specified event occurs on a particular user interface object, the interstate transitions described earlier occur. This scheme makes the state machine a callback for every IVIBuild user interface object and for every workspace window the user creates.

Separating the user interface presentation from functionality means that the presentation can be developed independent of functionality and the same functionality can be easily given a new presentation. New functionality can be added and tested in a straightforward way without worrying about its presentation.

Conclusion

HP IVIBuild was conceived with two objectives in mind: to be a powerful, easy-to-use tool to complement the HP IVI application program interface functions and to be the first API application and as such to provide feedback to the API development team. Both of these objectives have been accomplished. We believe that HP IVIBuild's functionality and designed-in extensibility based on an object-oriented architecture are among the first for tools of this type.

Acknowledgments

There were many challenges presented and many rewards gained in the development of HP IVIBuild. So many people added their inputs to HP IVIBuild that it is hard to mention them all. We would, however, like to thank Ron MacDonald (now at HP's Graphics Technology Division in Fort Collins, Colorado) who endured a year away from his home to work on HP IVIBuild. Every time a user draws a polyline or spline or makes a widget with HP IVIBuild, they will be using Ron's work. Thanks also go to Shiz Kobara of HP's Software Engineering Systems Division (SESD) who had the original idea that the user interface was a place where industrial designers could make a contribution. Thanks to Steve Anderson and Jennifer Chaffee of SESD who followed through on Shiz's idea while Shiz was busy working on HP OSF/Motif. Our users will see their work every time HP IVIBuild displays its user interface. Thanks to everyone who gave us their comments and encouragement.

Creating an Effective User Interface for HP IVIBuild

The HP IVIBuild user interface was a collaborative effort between the software engineers developing the code for the product and a group of industrial designers who understand the requirements of an effective graphical user interface.

by Steven R. Anderson and Jennifer Chaffee

AMONG THE PRESENT and potential customers for HP's computer systems are companies that are increasingly integrating computers into their manufacturing processes. However, the computer focus of these companies is more on solutions than on hardware and software development. To help provide these solutions on HP computer systems there are efforts within the company to encourage or enable independent software vendors (ISVs) to develop these software solutions. HP IVI from HP's Industrial Applications Center (IAC) is one such effort. Its purpose is to help ISVs build graphical user interfaces for their applications used in industrial applications.

Why the need for a graphical user interface? Many of the operators and users of computer-based systems in an industrial environment are not computer literate. They typically perform tasks like controlling an automated spray paint line, and the interfaces to the tools they use are typically knobs, dials, buttons and other physical and visual objects. A command line interface is a totally foreign approach for these people, and many of them refuse to deal with it. Whatever can be done to enable the interfaces to come closer to the users' current way of doing things is seen as having value. A graphical user interface is seen as having the greatest potential in making the interface familiar. Recent developments in user interface technologies[1] are very suitable for graphical user interfaces in industrial automation applications.

Background

HP IVIBuild is a tool that enables users to develop graphical user interfaces interactively. Therefore, it seemed appropriate that it should have a graphical user interface. For this capability the HP IVIBuild developers decided to use the graphical user interface components that were under development at HP's Interface Technology Operation (ITO) in Corvallis, Oregon. These components are commonly called widgets.[2] They include things like menus, scrollbars, pushbuttons, text-edit boxes, and radio buttons. They are the raw materials from which a graphical user interface is assembled. The HP IVIBuild team had no idea that using widgets would lead to collaborating with visual design professionals.

Neither did we, the visual design professionals, know about the HP IVI team. We are the usability design and engineering group of HP's Software Engineering Systems Division (SESD). We are former industrial designers who switched our design focus from designing hardware enclosures to the area of user interfaces, plus one graphic designer. At the time our division was developing what would become the HP SoftBench environment,[3] and we were also looking to ITO for the necessary widgets. Rather than passively waiting to see what they might provide, we were encouraged by our management to lend our professional expertise to the widget development, and ITO was open-minded enough to listen to some of our ideas.

We didn't begin with any proven graphic user interface expertise. We had done some design analyses of the leading graphical user interfaces. Also, coming from a background in which our experience and training forces us to process information visually gave us some ideas about how an effective graphical interface should look. And because our experience with software and computers was limited to being application users, we had some first-hand knowledge about the user interface requirements for users who are not software literate.

Basic Principles

Three principles have established the foundation for graphical user interfaces in recent years, notably in office-oriented applications. The first principle is that it is easier for most people to have their alternatives presented to them in a manner that allows them to make choices rather than having to remember all of the alternatives. Choosing a command from a menu is often easier than remembering it. The second fundamental principle is that making these choices by some means of direct manipulation is often preferred over typing in text commands. Pushing a button or dragging a file icon into a folder icon or a trash can are two examples of direct manipulation. Finally, the third principle is to use metaphors from the real world. For example, we know what to do with a pushbutton.

In our analyses of the many graphical interfaces existing today, one of the impressions we formed was how confusing they could be because of the flat and bland graphics. This is especially true in multiwindow environments in which there is a high degree of overlapping and the similarity of the graphic images seems to blend all the images together into one confusing mass. We thought that creating

greater visual distinctiveness between objects would significantly enhance a user's ability to keep things sorted out.

3D Appearance of Widgets

Our first attempts to express widgets graphically were with the traditional black lines on a white background. To get away from the sameness mentioned above, some of the widgets were drawn to look three-dimensional and to look and act like pushbuttons. It soon became apparent that the displays of the future would not be constrained to simple black and white, and that larger areas of solid color could be used. This was a significant breakthrough.

With the capability to use color, we added three colors to the black and white. By using light, middle, and dark versions of a color, we could make a button look very three-dimensional. This was achieved by making the top and left edges light, the flat surfaces the middle value, and the bottom and right edges dark. This technique makes it appear as though a light is shining on the button from the upper left. Another nice by-product of this technique is that by momentarily switching the light and dark colors when a button is selected, it actually appears to be pushed in. It was so effective that people got a little silly pushing buttons the first time they saw a working prototype.

People intuitively grasp the notion that if something appears to protrude, it can be pushed or selected to generate some action. Widgets that accept or display inputs appear to be recessed. Noninteractive things like labels are flat. Scrollbars are hybrids, with a recessed groove containing raised controls. Menu bars look like large buttons with several labels on them. When the mouse drags over a menu item, it appears to raise, transforming itself into a button. When a menu item is selected by releasing the mouse button, the feedback mechanism is the same shadow reversal the pushbutton uses to appear recessed. Fig. 1 shows the transition from a total 2D appearance to a full 3D appearance.

Most people found this 3D appearance appealing. It became a key factor in the subsequent adoption of the HP widgets by the Open Software Foundation (OSF) for their OSF/Motif standard user interface.[4]

A New Principle

The 3D appearance ends up creating a new fundamental graphical user interface principle: the visual separation and distinction of what we call *user space* and *interface space*. User space is where the user's inputs go, or where the user performs work. Examples are the space provided in a word processor for entering text, or the space provided in a paint program for creating images. It also includes those areas where the user is asked to input data like the name of a file.

The rest of the screen is the interface space, or the visual manifestations of the applications and/or the operating system. Included in this category are items like window frames, dialog boxes, tool panels, menus, and the metaphor-

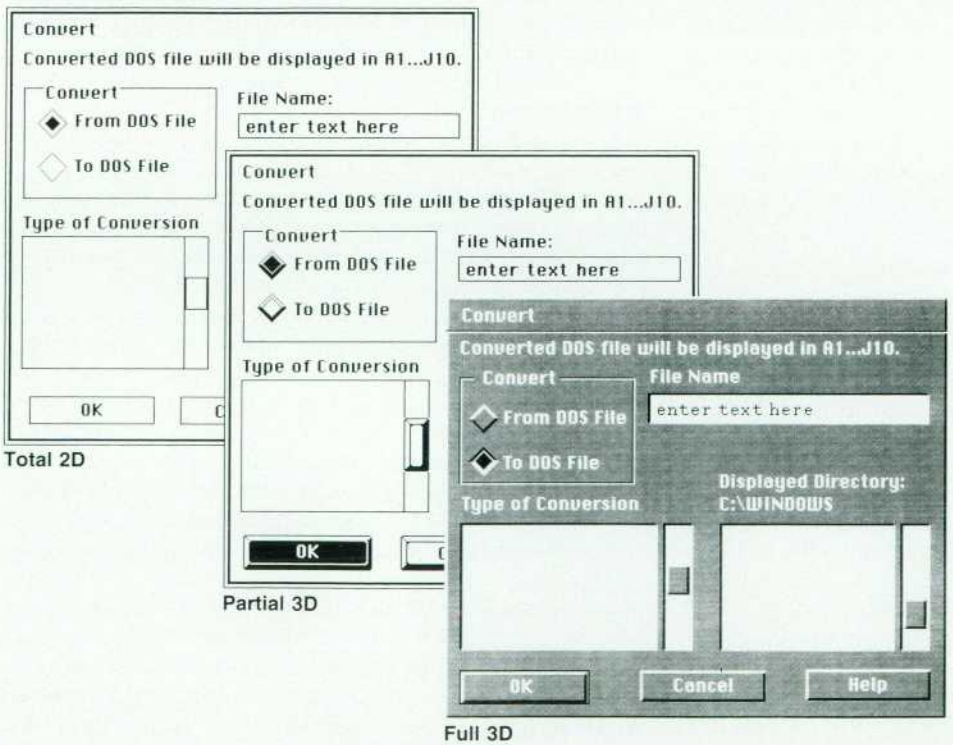

Fig. 1. *Transition from total 2D appearance to a full 3D appearance.*

ical desktop. The interface space, whether controlled by the application or the operating system, is where all of the 3D effect is found.

In office-oriented applications, which have been driving the graphical user interface movement to date, the 2D user space is usually dominant in terms of screen area. The main focus of these applications is generally to provide a tool that allows the user to create different forms of documents such as mail messages, memos, charts, spreadsheets, overhead slides, and newsletters. Based on these applications, the user space is perceived to be the WYSIWYG equivalent of some sort of paper document, whether a small notepad or a large drawing. It is predominantly two-dimensional, which is appropriate because the resulting documents are also two-dimensional.

There is an emergence of graphical user interfaces in which the interface space dominates because the main function of the applications is not document creation but some form of process setup and control. Examples include things like configuring and running a set of test instruments, or monitoring and controlling a complex temperature control system or an assembly line. HP IVIBuild is geared to create interfaces of this latter type. The 3D widgets (or OSF/Motif widgets) are particularly well-suited to this type of interface because the physical reality they convey is much closer to the mental model most people have of activities that are control-panel oriented. Fig. 2 shows one window for an office-oriented application and another for an instrument control panel.

HP IVIBuild before Redesign

In the early stages of development, the HP IVI team used the initial version of the widget code from HP's Information Technology Operation. The early results of their using this code produced the 3D appearance shown in Fig 3. Unfortunately the 3D effect was largely lost and the user interface was hard to understand. This early result was not a surprise because the HP IVIBuild team had not yet had enough experience with widgets and consequently had little notion of how to achieve and use the 3D effect. They were also unfamiliar with many of the standard techniques and practices for creating graphical user interfaces.

Our group had concurrently been using the 3D widgets with our own HP SoftBench tools. That successful experience plus the acceptance of HP widgets for OSF/Motif gave us a certain amount of credibility. As a result we soon found ourselves in contact with the HP IVIBuild team. Like our experiences with the ITO team in the development of widgets, the HP IVIBuild people were very open-minded in letting us get involved with their product.

HP IVIBuild was different for us in that it not only uses conventional widgets to create a graphical user interface, but it can also create graphic objects that behave like widgets. What this means is that buttons and scrollbars can be supplemented with graphic representations of objects that can change to reflect current status. For example, a graphic image of a storage tank can change to show the current level of the liquid it contains, or an assembly line schematic can be changed to reflect the status of each work cell. The output of HP IVIBuild can range from simple windows with menu bars and dialog boxes to very complex control-panel-like layouts with animated graphics and numerous controls. These capabilities were not obvious in the original interface shown in Fig. 3.

The Structure of HP IVIBuild

The HP IVIBuild user interface is divided into three parts: a utility box, a tool box, and a workspace.

The Utility Box. This area holds the menu bar, a prompt window, several status indicators, and some commonly used commands in the form of pushbuttons.

The Tool Box. This area is like a palette of various graphic or widget creation tools. It has three modes: graphics, widgets, and models. The graphics mode functions like a typical paint program, displaying numerous drawing tool buttons as well as mechanisms for displaying and selecting items such as colors, patterns, and line weights. The widget mode is used for creating and specifying the widgets. The models mode is used to get access to models, which are templates or libraries of previously created work. Fig. 4 shows the utility box and tool boxes at an early point in the design stage of HP IVIBuild.

The Workspace. This is the area in which the user does the work of building a user interface. In this area graphic or widget objects are put together on a kind of three-dimensional sheet of paper. After assembly, they are stored away for use as finished products or as models for reuse or modification. For example, a simple dialog box might be used as a template for other dialog boxes, eliminating the need to start each one from scratch.

Collaboration

The early efforts by the industrial designers focused on sorting out the functionality found in each of the HP IVIBuild areas and then finding reasonable ways of presenting each area. The utility box and the tool box visual layouts received the most attention. One of the first steps was determining the menu structure in the utility box. Certain conventions and many examples exist in industry showing how applications organize and perform activities like editing and filing—for example, the locations of commands like cut, copy, paste, and quit in a word-processing package. And certain conventions exist in terms of dialog box layout, like where the OK, cancel, and help buttons should go. We followed accepted general practices wherever possible, and tried to develop acceptable solutions where no previous models existed.

The tool box with its various modes was probably the most complex job. The final layout chosen for the tool box owes many of its approaches to showing status and offering choices or functions to existing de facto standards for paint programs. There were instances where we were forced by technical limitations to deviate from these standards. For example, a simple draw tool like the one used to draw a rectangle typically requires a decision about whether the rectangle is to be filled in or left as an outline. A typical solution is to have one button with a rectangle on it, with the left half hollow and the right half filled (what looks like one button is in fact two buttons). In our case the widgets wouldn't allow that approach, so we ended up with a separate button to turn the fill function on or off. Fig. 5 shows the design recommendation for the utility and

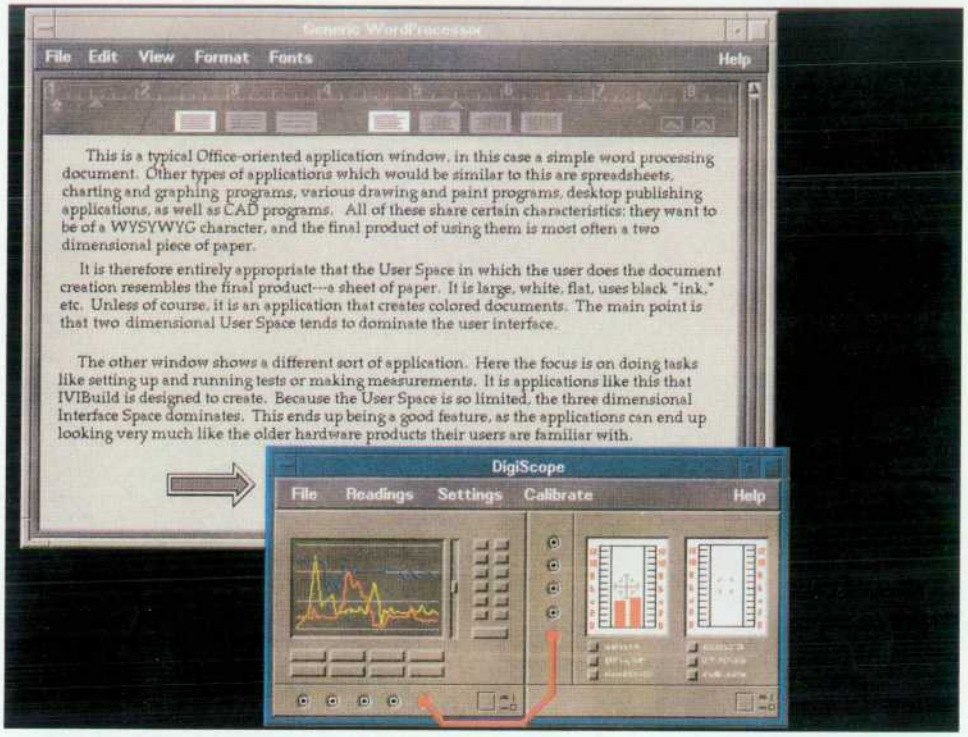

Fig. 2. *One window with a typical 2D office-oriented application and the other window showing a 3D instrument control panel.*

tool boxes at a later stage in the development.

Colors were another area where the designers had something to contribute. We had some color schemes in hand from our earlier work on widgets as well as from our work with HP's SoftBench product. This greatly simplified the tricky decisions required to convey the 3D quality of widgets. We provided the color names and RGB values that had to be assigned to each widget component to make the 3D effect work and provide a pleasant overall interface.

Fonts were also important. Graphical user interfaces in general, and the 3D widgets in particular, are very much dependent on good fonts to be successful. While the popular notion of a graphical interface centers on icons, most of the work is still done with words, and good proportionally spaced fonts make words work better. The HP IVIBuild team decided to use some display fonts that had been created by HP expressly for 3D widgets. These fonts provided both behavioral benefits (text properly centered

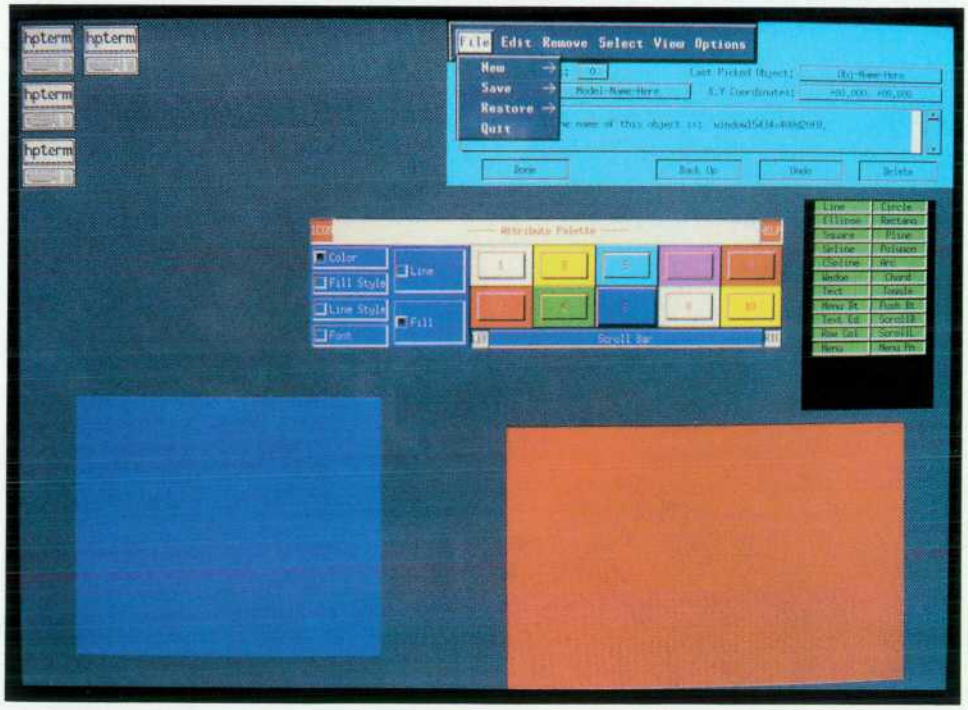

Fig. 3. *A very early version of HP IVIBuild when the design team first began to use widgets.*

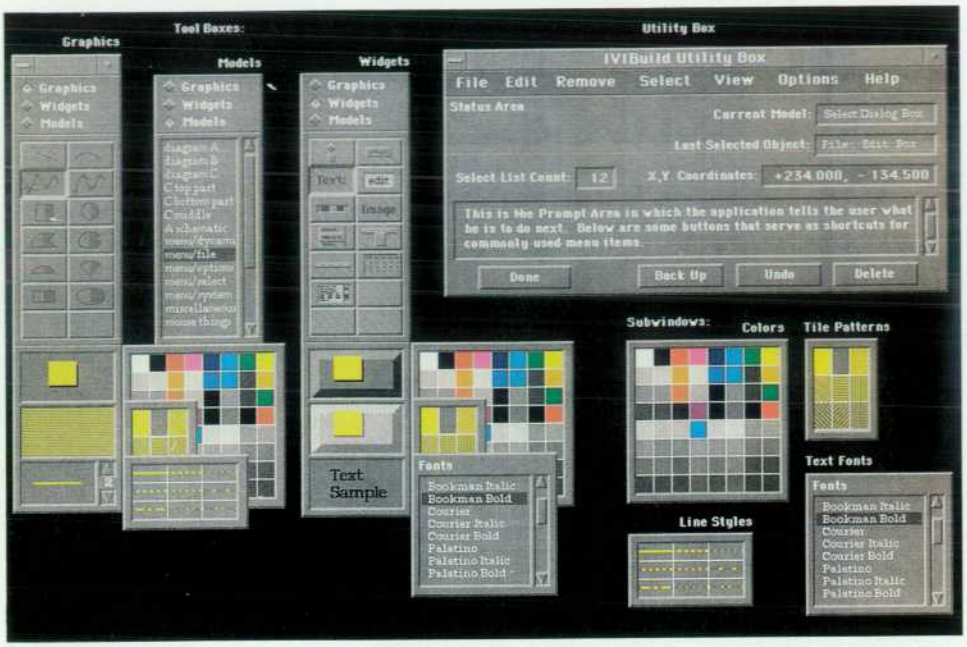

Fig. 4. *The visual designers' first proposal for the HP IVIBuild user interface.*

in widgets, text baselines lined up, etc.) and a consistent, high-quality look.

The designers also created all of the bit maps and icons associated with the tool boxes and other aspects of the product. One challenge with many of the tool box buttons, especially for those in the widgets mode, was to express the 3D nature on a small scale and with only two colors. The illusion of using three colors was achieved by using a light and a dark color and then introducing a dithered pattern that the eye blends together to form a third color (see Fig. 6).

The final area of collaboration was to do something visual and graphical to help explain and sell HP IVIBuild. Some sample screens were created that express how HP IVIBuild can actually be used. With just a little prompting on how to use the 3D effect, a designer used HP IVIBuild to create two sample screens for each of seven potential application areas. These compelling images, achieved through the use of the actual tool, have done more to explain HP IVIBuild and its capabilities than a volume of marketing brochures. One of these sample screens is shown in Fig. 2 on page 8.

Conclusion

We learned a few things as a result of this collaborative exercise. One is that experts often have problems communicating their concepts and ideas to nonexperts. In this case we had two groups of experts. We found that it was important to have a main conduit or interpreter between the user interface designer and the rest of the software team. Without someone to answer all of the questions the

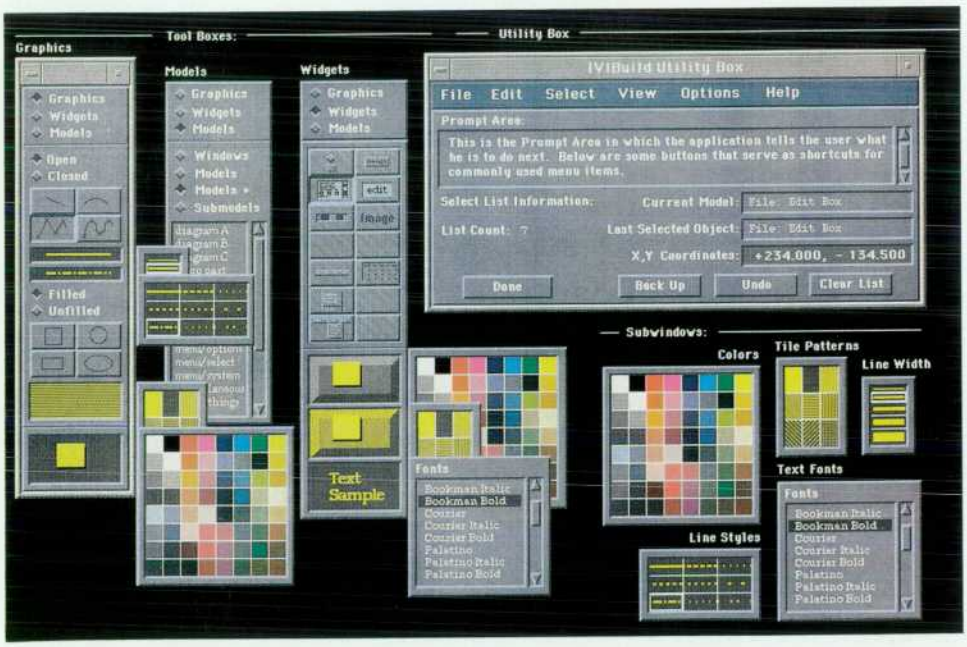

Fig. 5. *A later version of the user interface after incorporating some of the implementation limitations.*

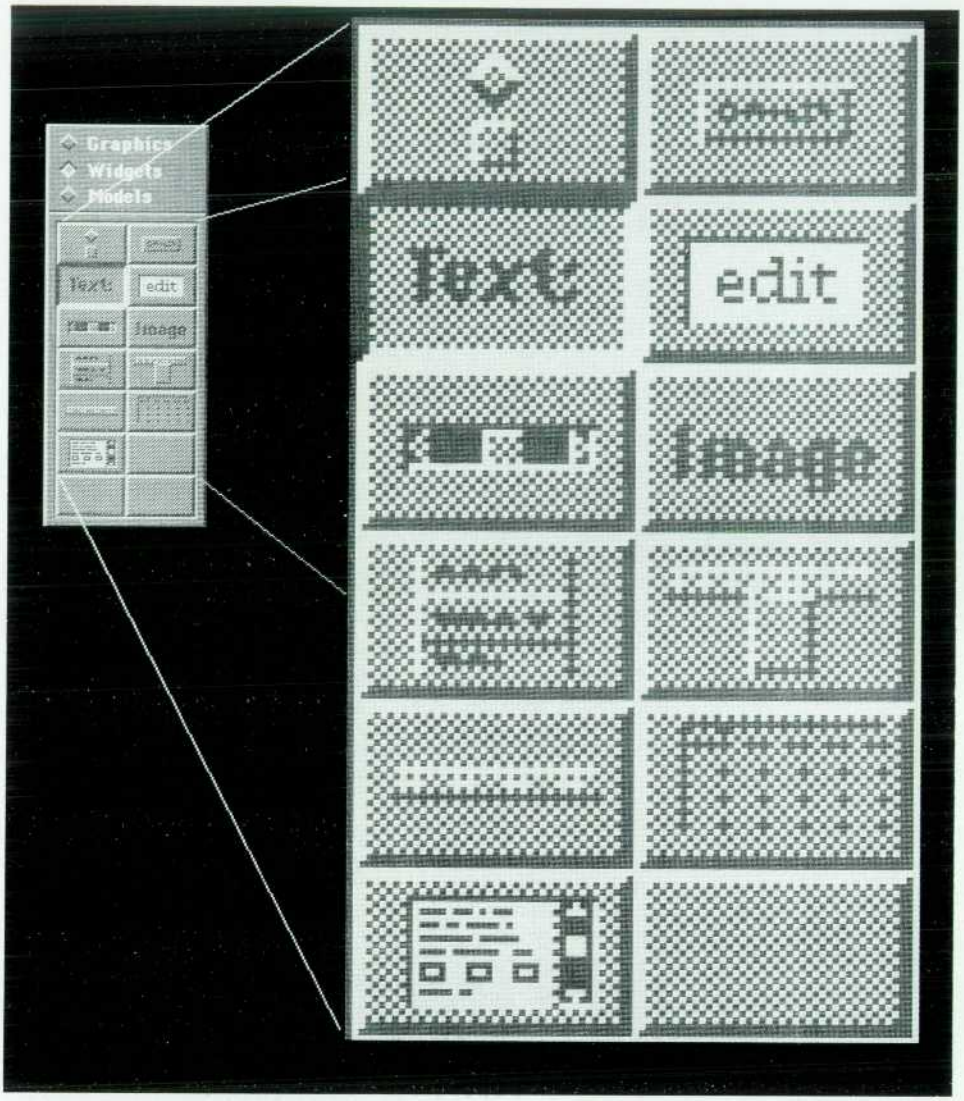

Fig. 6. *Achieving the 3D effect with only two colors.*

user interface designer asks, and interpret the various dialogs with the team members, the communication process really breaks down. One designer interfacing with a half-dozen individual team members means a half-dozen different interfacing styles.

Another lesson we learned is how important it can be to have an early vision of what you are trying to do. Tools exist that enable designers to create this vision and user scenarios quite quickly. The power and usefulness of these visuals should not be underestimated. They are powerful catalysts for people's thinking and communication. Once these are analyzed, discussed, and modified, the product is better understood by all concerned. Only at this point should the interface coding begin. The mistake should not be made of bringing the visual design help in at the very end to fix up the icons. Chances are the flaws go far beyond cosmetic graphics, and at this point the investment has been so great that significant changes are nearly impossible.

Acknowledgments

Acknowledgments are due some of the key people who are responsible for this successful collaboration. First, to Steve Joseph and Chuck House of SESD, for letting us work outside of our own division. Both of them have been amazingly farsighted in encouraging us to work wherever we can use our expertise to help HP product development. At HP's Industrial Applications Center (IAC) where HP IVI was developed, thanks go to section manager Chuck Robinson, project manager Vicki Mosely, and team members Steve Witten, Pam Munsch, Scott Anderson, and Ron Macdonald for their patience and openess. And within IAC mrketing, special thanks to Dushyant Sukhija and Andy Lerner for their enthusiastic adoption of visual selling techniques. Finally, a special acknowledgment to the other members of the industrial design team, Barry Mathis and Shiz Kobara.

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Authors

October 1990

6 HP IVI

Roger K. Lau

Roger Lau, a technical marketing engineer at HP's Industrial Applications Center, provided technical support for HP IVI. Roger joined HP's Data Systems Division in 1981. He has worked as a development engineer and a technical lead in the development of the HP Advanced Graphics Package, the HP Device Independent Graphics Library, the HP Manufacturing Automation Protocol pilot for General Motors Corp., and the HP Graphics Interface System. Roger earned a BA degree in microbiology in 1976, an MS degree in microbiology in 1978, and an MS degree in computer science in 1981, all at the University of Hawaii. Born in Honolulu, he lives in San Jose, California, where he enjoys volleyball and ballroom dancing.

Mark E. Thompson

Software engineer Mark Thompson joined HP's Data Systems Division in 1980, where he worked on disk diagnostics and utilities, I/O drivers for HP 1000 computers, and a quality decision management program. For the HP IVI project, he was responsible for graphic objects, the error handler, and the quality function deployment analysis. His professional interests center around 2D and 3D graphics. Mark received his BS degree in computer engineering from Boston University in 1980. Born in San Francisco, California, he lives in Berkeley. His interests include automobile restoration, beer making, photography, bicycling, gardening, hiking, camping, and audio electronics.

11 HP IVI Toolkit

Mydung Thi Tran

Software engineer Mydung Tran was responsible for widget development, testing, and native language support for the HP IVI project. She joined HP's Industrial Applications Center in 1988. Mydung has authored or coauthored five technical articles on distributed processing, particle dosimetry, space radiation, and nuclear track detectors. Before joining HP, she was a research physicist at the University of California at San Francisco, and a graduate assistant at Lawrence Berkeley Laboratories. A member of the ACM, her professional interests include computer graphics, parallel processing, and networking. She received her BS degree in physics in 1975 from the University of San Francisco and her MS degree in computer science from San Francisco State University in 1989. Born in Saigon, Vietnam, she is married, has a son and a daughter, and lives in San Francisco.

David G. Wathen

User interface design, graphics, and artificial intelligence are the professional interests of David Wathen, a software engineer who developed enhancements for the HP IVI project. He joined HP's Industrial Applications Center in 1989, shortly after he received a BS degree in computer science and applied mathematics from the University of Colorado at Boulder. Before joining HP, he was a software designer for the National Center for Atmospheric Research (NCAR), where he built an X11 window interface to NCAR graphics. David was also an advanced interface intern at US West, where he worked on future telephone projects. Born in Littleton, Colorado, he resides in Sunnyvale, California, where he enjoys Tae Kwon Do, skiing, 4-wheel driving, backpacking, and traveling.

21 HP IVI API Design

Pamela W. Munsch

Pam Munsch, a software development engineer on the HP IVI project at HP's Industrial Applications Center, worked as a development engineer on an IC testing project shortly after she joined HP's Santa Clara Division in 1983. She is now an R&D project man-

ager working on HP IVI. Pam received her BS degree in computer science in 1983 from the University of California at Santa Barbara. She is married, lives in the city of her birth, San Jose, California, and enjoys playing volleyball.

Warren I. Otsuka

As an R&D software engineer at HP's Industrial Applications Center, Warren Otsuka was responsible for input handling and widget objects for the HP IVI project. After joining HP's Data Systems Division in 1978, he worked on support for the HP F/1000 forms management tool and HP F/1000/HP-UX products. Before joining HP, Warren was a project lead for user interface development and an engineer on a document project for Docugraphix, Inc., and he provided system support for the STAR-100 operating system at Control Data Corporation. He earned a BS degree in computer science from the California State University at Chico in 1972. Born in Kona, Hawaii, Warren is married, has a daughter, and lives in Campbell, California. He enjoys family activities, reading mysteries, and photography.

Gary D. Thomsen

Software development engineer Gary Thomsen, who joined HP's Data Systems Division in 1979, helped design widget classes for the HP IVI project. Before that, as an R&D software engineer, he provided support for the HP 1000 Series Forms/1000 product, and as an R&D product design engineer, he designed the HP 1000 Series A hardware packaging. Gary earned his BA degree in mathematics from San Jose State University in 1977. He is married, lives in San Jose, California, and enjoys softball, biking, and woodworking.

32 HP IVIBuild

Steven P. Witten

The principal architect of the HP IVIBuild portion of the HP interactive Visual Interface, Steve Witten implemented the state machine and window and model handling for the project. Now an R&D engineer at HP's Industrial Applications Center, he joined HP's Data Systems Division in 1978. Initially, he worked on Datacap/1000 and supported HP 307x terminals, and then developed an energy management system for HP using the PMC/1000 system. Before joining HP, he worked for Environmental Research and Technology, Inc., where he compiled a data base of airborne sulfate/particulate measurements for the Electrical Power Research Institute's study of acid rain. Steve is a frequent contributor to INTEREX, the HP users group, writing technical articles on object-oriented programming. A member of the Institute of Industrial Engineers, his professional specialty centers around object-oriented technology. He received a BS degree in computer science in 1974 and an ME degree in industrial engineering in 1976 from the California Polytechnic State University in San Luis Obispo. Born in Bakersfield, California, Steve is married, has two daughters, and lives in San Jose. His hobbies include computers and reading detective novels.

Hai-Wen L. Bienz

Hai-Wen Bienz was responsible for the development of the graphic objects and dynamics in the HP IVI application program interface. She joined HP in 1985 and served as a publications engineer at HP's Santa Clara Division, and later as a marketing engineer for the Strategic Grants program at HP Laboratories. Hai-Wen's professional interests include designing user interfaces and software tools to enhance productivity. Before joining HP, she was a coop student and engineer at General Motors Corp., where she developed real-time digital control systems. Hai-Wen earned a Bachelor's degree in electrical engineering from the General Motors Institute in 1983 and an MS degree in electrical engineering from the University of Illinois at Urbana-Champaign in 1984. She is married and lives in Naperville, Illinois. Her interests include mountaineering, skiing, photography, cooking, and hiking.

39 HP IVIBuild User Interface

Steven R. Anderson

Visual interface designer Steve Anderson helped design the user interface for the HP IVIBuild product. He joined HP's Calculator Products Division in 1976 and was responsible for the industrial design package for the HP 9845 computer/controller and computer system furniture products, including the HP 92214 CAD worktable. Now a lead designer on the HP VUE graphical environment for HP-UX workstations, Steve's professional interests include making computers visually appealing and fun to use. He is named as an inventor on an industrial design patent for a Xerox copier, coinventor of a product design layout patent on a color printer concept from HP Laboratories, and coinventor on a patent application for HP 3D widgets and extensions. Steve received a BS degree in industrial design from the University of Bridgeport in 1966. Born in Hibbing, Minnesota, he is married, has two children, and lives in Mountain View, California. He enjoys playing golf at dawn on Sundays, bicycling to work, and activities with his children.

Jennifer Chaffee

Jennifer Chaffee worked on the user interface for the HP IVIBuild product at HP's Industrial Applications Center. She joined HP in 1988 and worked on HP OSF/Motif and the HP NewWave Office. Before coming to HP, she worked in the industrial design and user interface department of the Xerox Corporation copier division. A 1985 graduate of the Rochester Institute of Technology with a BFA degree in graphic design and art history, Jennifer's professional interests include the visual design of computer user interfaces. Born in Fort Worth, Texas, she lives in Sunnyvale, California. She enjoys painting, pastels, pottery making, backpacking, traveling, and photography.

49 BaFe Preselected Mixers

Michael J. Levernier

Development engineer Mike Levernier was responsible for the design of the HP 11974 filter drive circuitry and for HP 11974 test development. He joined HP's Signal Analysis Division in 1984 as a manufacturing engineer responsible for the HP 8557A and HP 8559A spectrum analyzers. Following that, he worked on the microwave and RF front-end modules of the HP 70000 modular spectrum analyzer family. He also served as an HP regional sales development engineer. Mike received his BS degree in 1983 in electronic engineering from California Polytechnic State University, San Luis Obispo, and his MS degree in 1986 in electrical engineering from Stanford University. Born in Sacramento, California, he lives in Windsor, California. His hobbies include windsurfing, skiing, and racquetball.

Robert J. Matreci

Bob Matreci served as R&D project manager during development of the HP 11974 preselected spectrum analyzer RF sections. He joined HP's Signal Analysis Division in 1978 as a production engineer in microwave microelectronics. After transferring to the R&D lab, he developed millimeter-wave accessories for spectrum analyzers, including the HP 11970 Series waveguide harmonic mixers. Before joining HP, he developed avionics test equipment for weather radar. Bob has authored two technical papers and is named an inventor on a patent related to the preselected RF sections product. He is a member of the IEEE and is the program chairman of the local subsection. Born in Chicago, Illinois, Bob is married and resides on Riebli Mountain near Santa Rosa, California. His interests include sailing on San Francisco Bay and near the Northern California coast, and volunteer testing of emergency beacons for NASA's Search and Rescue Satellite (SARSAT).

59 Hexagonal Ferrites

Dean B. Nicholson

For the past eight years, Dean Nicholson has grown barium ferrite single crystals, processed them into spheres, and designed filters using the spheres. Since he joined HP's Microwave Technology Division in 1980, he has also been responsible for characterizing alumina and sapphire substrates. He received his BS degree in 1980 with dual majors in electrical engineering and materials science engineering from the University of California at Berkeley. Dean is an author or coauthor of four technical papers on barium ferrite-tuned filters and oscillators. He is named an inventor on a patent on the four-sphere filter configuration that is part of the HP 11974 spectrum analyzer RF sections product. Born in Orange, California, Dean is married, has three daughters, and lives in Windsor, California. He enjoys diving, hiking, and camping.

62 HP DIS

Kent L. Garliepp

Specializing in computer-aided manufacturing, Kent Garliepp worked on design, development, and testing of HP DIS software for HP 9000 computers as a member of HP's Industrial Applications Center in Sunnyvale, California. After joining HP in 1959, he provided computer support for the solid-state laboratory of HP Laboratories, and IC manufacturing software support at HP's Cupertino Integrated Circuits Operation. More recently, he helped design software for truck manufacturing at HP's Advanced Manufacturing Systems Operation. Born in Palo Alto, California, Kent is married, has four children, and lives in Capitola, California. His interests include bicycling, radio-controlled models, and water-color painting.

Kathleen A. Fulton

After joining HP's Engineering Productivity Division in 1984, software engineer Kathy Fulton helped develop the equipment control portion of HP's Semiconductor Productivity Network. She also designed and coded the configuration, initialization, and run-time portions of the HP DIS product, and is now testing and maintaining HP Sockets software at HP's Industrial Applications Center. Before joining HP, Kathy was a semiconductor fabrication engineer at Burroughs Corp. and a software development engineer at Trilogy Corp. and Amdahl Corp. A member of the IEEE, she received her BA degree in 1975 in applied physics and information science with a specialization in computer science from the University of California at San Diego. Born in Reno, Nevada, Kathy is married and lives in Cupertino, California. Her interests include traveling to unusual locations, reading science fiction, and quilting.

Irene Skupniewicz

For the past four years at HP, Irene Skupniewicz has worked as an R&D software engineer in the development of manufacturing applications. Currently, she is in the Manufacturing Applications Group working on the Device Interface System and Software Integration Sockets, two products that are part of HP's industrial precision tools for HP 9000 computers. Irene earned a BS degree (1981) in industrial engineering from the University of Wisconsin, and an MS degree (1987) in electrical engineering from Carnegie-Mellon University in Pittsburgh. Before joining HP, she worked with Unimation/Westinghouse in Pittsburgh to develop robotic systems. Born in Racine, Wisconsin, Irene lives in Cupertino, California. For many years, she has been a "die-hard" runner and enjoys meeting other HP people through her membership in the HP Running Club.

John U. Frohlich

As a member of the software development team at HP's Industrial Applications Center, John Frohlich helped develop the HP DIS product. He joined HP in 1976 at the company's Optoelectronics Division, and helped develop machine language programs for calculator-based systems to test LED display devices. He also has worked on several versions of the RTE operating system for HP 1000 computers and on ATS/1000 software. John received his BSEE degree in 1963 at the Lucerne State College of Technology in Switzerland. He is a member of the IEEE. Born in Switzerland, he lives in Cupertino, California, and enjoys mountain hiking, biking, and listening to old jazz recordings.

73 R, L, C Measurements

Asad Aziz

Now a marketing account manager for HP's Circuit Technology Group, Asad Aziz was previously in R&D, where he worked on the design, layout, modeling, and electrical model verification of the PCX CPU package. Before that, he worked on packaging R&D for HP PA-RISC computers, and on TAB design and electrical modeling. Asad joined HP's Colorado Integrated Circuits Division in 1985, shortly after he graduated from Brigham Young University with a BSEE degree in 1984. He received an MBA degree in 1990 from the University of Denver. A member of the IEEE, he has coauthored two technical papers on packaging. Born in Lahore, Pakistan, Asad is married and lives in Fort Collins, Colorado. He enjoys squash, bicycling, and windsurfing.

Ravi Kaw

Ravi Kaw developed a methodology to measure R, L, and C parameters in VLSI packages using coaxial probes rather than custom-designed boards. Since joining HP in 1982, he has served as a product engineer for DRAM and math chips and as a semiconductor process engineer, and has worked on package measurements and modeling research. Before joining HP, Ravi was a lecturer at Kashmir University and an engineer at the Jet Propulsion Laboratories and Fairchild Semiconductor Corp. He is the author of 14 technical articles on device physics, device modeling, packages and

systems, and measurement methods. His work has resulted in two pending patents on packaging structures and systems and measurement methods. Ravi is a member of the IEEE and the International Packaging Society. He received his BE degree in 1966 in electronics and telecommunications from Jabalpur University, his MSEE degree in 1972 in microwave solid-state devices from Marquette University, and his PhD degree in 1978 in solid-state electronics, quantum electronics, and microwaves from the University of California at Los Angeles. Ravi is a member of the board of directors of a local Hindu community and cultural center, and a Sunday school teacher. Born in Srinagar, Kashmir, India, he is married, has two children, and resides in San Jose, California. He enjoys jogging, gardening, hiking, and reading.

David W. Quint

Before Dave Quint joined HP's Desktop Computer Division in 1979, he helped design nuclear reactor control systems for Westinghouse-Bettis Atomic Power Laboratories. As an HP R&D design engineer, he developed tape automated bonding (TAB) and pin-grid array (PGA) packaging for VLSI circuits. He is now an R&D engineer working on integrated circuit packaging at HP's Colorado Integrated Circuits Division. Dave's work has resulted in two patents, one describing a method of sampling a 100-GHz optical pulse stream, and another for a method of depositing tungsten for integrated circuit interconnects. His professional interests include integrated circuit process engineering, electromagnetic fields, circuit analysis, and optical electronics. He published a paper in the Journal of Applied Physics while at MIT, and has coauthored three conference papers on electronic packaging. He received his BSEE degree in 1972 and MSEE degree in 1976 from the University of Wisconsin at Madison, and earned a PhD degree in 1979 from the Massachusetts Institute of Technology. Dave served as a weather observer in the U.S. Air Force from 1963 to 1967, attaining the rank of sergeant. Born in Barron, Wisconsin, he is married, has two boys and a girl, and resides in Fort Collins, Colorado. His hobbies include weight lifting and taking karate lessons with his children. Dave says they hold advanced belts in the martial arts, but he's still working on the basics.

Frank J. Perezalonso

Frank Perezalonso specializes in hardware design engineering and analog circuit design and measurements. He joined HP Laboratories in 1984 as a semiconductor process technician, and is now a member of the technical staff of HP's Circuit Technology Group. He worked on the electrical characterization of the high-performance HP 408C PGA integrated circuit package. In the past, Frank was involved in E-beam lithography process development, evaluation and test of HP's membrane probe card, and test methods for the electrical characterization of IC packages. Before he joined HP, he worked on semiconductor processing for Fairchild Semiconductor Corp. and as an instructor in math, physics, and semiconductor processing at Foothill College in Los Altos, California. He studied semiconductor processing at Foothill College, received a BSEE degree in 1985 from the University of Santa Clara, and expects to receive his MSEE degree in December. Born in Managua, Nicaragua, Frank is married, has a daughter, and lives in San Jose, California. He enjoys sports and teaching.

78 Statistical Simulation

Chee K. Chow

Manufacturing development engineer Chee Chow specializes in computer-integrated manufacturing, manufacturing data bases, and analog and microwave circuits. He joined HP's Santa Clara Technology Center in 1984 and has done research in statistical circuit simulations for circuit designs. He recently transferred to HP's Microwave Semiconductor Division. In the past, Chee worked on bipolar high-speed circuits at HP, and researched coal conversions and materials at Washington State University, where he received his PhD degree in 1974 in physical chemistry. He also earned an MS degree in 1984 in electrical engineering from Oregon State University. Chee is the author of 15 technical articles on fuel processing, physical chemistry, and electronics.

82 Air Flow Analysis

Kent P. Misegades

As manager of computer fluid dynamics applications at Cray Research, Inc., Kent Misegades collaborated with HP on airflow simulation in the HP 9000 Model 850 computer. At Cray Research, he is responsible for all fluid dynamics-related applications in the aerospace, automotive, metals, electronics, and chemical industries. His experience also includes work as an aerodynamicist for Dornier GmbH in West Germany from 1980 to 1984. A member of the AIAA, Kent's professional interests include aircraft design and fluid mechanics. He is a graduate of Auburn University with a BSc degree (1979) in mechanical engineering, and has an ME degree (1980) in fluid dynamics from the von Karman Institute in West Germany. Born in Los Angeles, California, Kent is married, has three children, and resides in Eagan, Minnesota. His hobbies include aircraft design and radio-controlled sailplanes.

Vivek Mansingh

Since joining HP's Systems Technology Division in 1987, Vivek Mansingh has performed research and development in thermal management of electronic equipment in the company's mainline systems lab. Using finite-element modeling, he analyzed three-dimensional air flow in the HP 9000 Model 850 computer. Before joining HP, Vivek taught at Lehigh University from 1986 to 1987. A member of the ASME, the IEPS, and the CHMT, he has authored or coauthored 12 technical publications on thermal fluids, and is named an inventor on a pending patent. He earned his MS and PhD degrees in 1986 from Queen's University in Canada, studying mechanical engineering and specializing in thermal fluids. Born in Fatehpur, India, Vivek is married, has two children, and lives in Santa Clara, California. He enjoys traveling with his family and singing Indian music with a professional group. His hobbies include jogging, tennis, and badminton.

26.5-to-75-GHz Preselected Mixers Based on Magnetically Tunable Barium Ferrite Filters

A new resonator material—barium ferrite—and a new four-sphere design are featured in a series of magnetically tunable preselection filters for the millimeter-wave frequency range.

by Dean B. Nicholson, Robert J. Matreci, and Michael J. Levernier

THE NEED FOR HIGHER PERFORMANCE has driven the frequency ranges of systems and components from the microwave range (under 30 GHz) into the millimeter wavelengths (30 to 100 GHz). Moving to higher frequencies makes it possible, for example, to increase the antenna gain of small reflectors and to improve the spatial resolution of imagers. The benefits of the move to millimeter-wave bands are being felt in many fields, especially communications, remote sensing, and defense.[1]

The spectrum analyzer, a calibrated receiver with variable resolution, is an important basic tool for testing and troubleshooting such systems. Microwave spectrum analyzers use advanced technology to provide accurate, unambiguous frequency-domain measurements. Hewlett-Packard has extended these measurements into the millimeter-wave bands.

A new series of preselected spectrum analyzer RF sections, the HP11974 Series preselected mixers, makes millimeter-wave spectrum analyzer measurements faster and easier by removing image and multiple responses from the spectrum analyzer display, thereby eliminating the need for complicated signal identification routines. Each RF section consists of a mixer to down-convert millimeter-wave signals into the intermediate frequency range of HP microwave spectrum analyzers, and a magnetically tuned preselection filter to remove unwanted signals. The preselection filter uses barium ferrite resonator material, doped so that it starts resonating at the beginning of the waveguide band (see article, page 59).

Table I lists the four preselected RF sections and their frequency ranges. Each RF section covers a full waveguide band (±20% bandwidth), one of the four standard bands from 26.5 to 75 GHz.

The HP 11974 Series preselected mixers are compatible with the HP 8566B spectrum analyzer, the HP8563A portable spectrum analyzer, the HP 70000 modular measurement system with the HP 70907B external mixer interface module, and other HP microwave spectrum analyzers. They provide a displayed average noise level at 10-Hz bandwidth that is lower than −106 dBm in the A, Q, and U bands and lower than −95 dBm in the V band. Image rejection is better than 55 dB in all four bands.

Table I
HP Millimeter-Wave Preselected Spectrum Analyzer RF Sections (HP 11974 Series Preselected Mixers)

RF Section	Waveguide Band	Frequency Range
HP 11974A	A	26.5 to 40 GHz
HP 11974Q	Q	33 to 50 GHz
HP 11974U	U	40 to 60 GHz
HP 11974V	V	50 to 75 GHz

Methods of Extending the Frequency Range

There are three principal ways to extend the frequency range of a microwave spectrum analyzer. The first method, shown in Fig. 1a, uses a classic superheterodyne receiver front end. A tracking preselector and a local oscillator (LO) both sweep the same frequency span, separated by the intermediate frequency (IF). The preselector prevents spurious responses, such as images or intermodulation products, from being displayed. The LO must be phase-locked and have reasonably low phase noise. To use this method, high-Q resonators and active devices maintaining negative resistance across the full waveguide bands would have had to be developed. The design would have been intricate and expensive. These technological difficulties eliminated this method from consideration for the HP 11974 Series. Fig. 2 shows where this type of millimeter-wave extender would interface with the mainframe microwave spectrum analyzer.

A block down-converter, shown in Fig. 1b, eases the local-oscillator problem by using one fixed oscillator per band instead of the swept LO of the superheterodyne receiver. With this down-converter, input RF frequencies are converted to an identical but lower frequency span (swept IF). The swept IF can be arranged to be within the range of the microwave spectrum analyzer. Even though the resonator and the active devices are operated at a single frequency, designing for performance and cost still poses a formidable problem. Also, this method lacks a tracking preselector, so the first mixer is subject to distortion caused

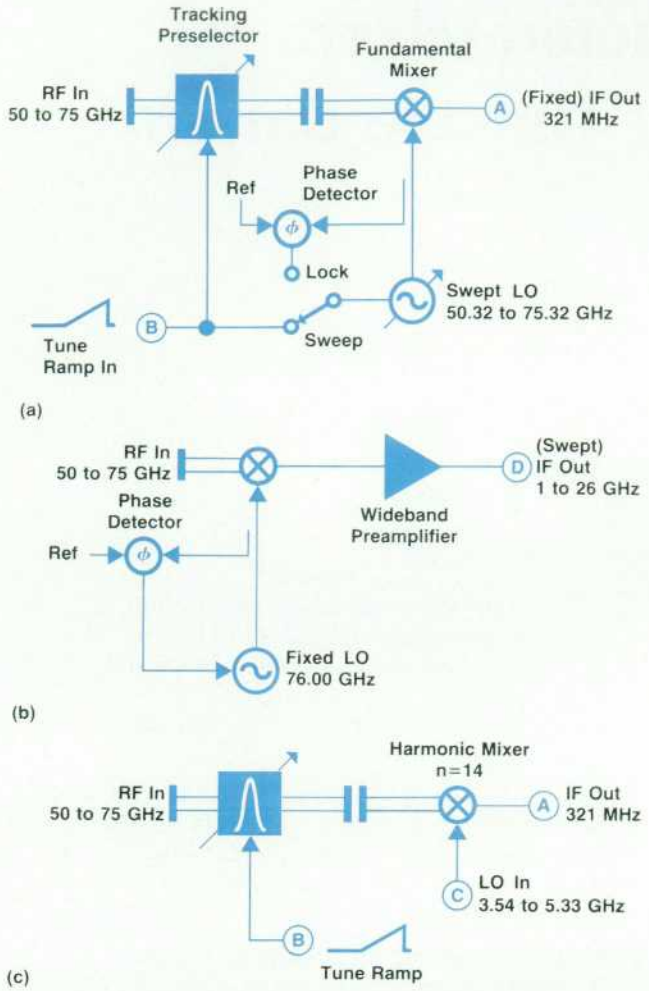


Fig. 1. *Three types of RF sections for extending the frequency range of a spectrum analyzer. The letters A, B, C, and D refer to Fig. 2, which shows where these RF sections connect to the spectrum analyzer. (a) The superheterodyne RF section uses a swept preselector and a swept local oscillator (LO). The phase-locked loop is used to set the beginning of the LO sweep accurately. (b) The block down-converter has a fixed LO and a swept intermediate frequency (IF). (c) The harmonic mixer version of the superheterodyne RF section.*

by multiple signals and even single input signals. The wide span of the IF can cause another problem. It requires a very wide-bandwidth IF amplifier to improve the sensitivity of the microwave analyzer, which is used as a variable IF strip.

The preselected harmonic mixer version of the superheterodyne front end, shown in Fig. 1c, provides a reasonable compromise. The preselector protects the mixer from spurious responses. The mixer, a harmonic type, uses a millimeter-wave harmonic of the existing microwave LO in the analyzer. The conversion loss of such a harmonic mixer exceeds that of the fundamental harmonic mixer shown in Fig. 1a, but the design effort goes into the preselector, which is a passive component and therefore somewhat easier to design than a millimeter-wave LO. (Of course, once the resonators for such a preselector are available, a wideband oscillator may be possible if the active devices can be obtained.)

Block Diagram

The method of Fig. 1c was chosen for the HP 11974 Series preselected mixers. Fig. 3 shows the HP 11974 block diagram. The RF signal that is to be down-converted to IF enters the waveguide flange of the tunable preselector shown in Fig. 3, then goes to the isolator and the HP 11970 Series harmonic mixer. Electromagnets in the preselector develop a magnetic field, which tunes the preselector. The scaling electronics transforms the tune ramp voltage of the spectrum analyzer into magnet current.

The unbiased harmonic mixer was developed previously[2] to extend spectrum analysis into the millimeter-wave range. If used without a preselector, the mixer converts the RF signal to an IF whenever an LO harmonic sweeps past the RF. However, the horizontal frequency scale is only calibrated for a single harmonic of the LO, the 14th for the V-band example shown in Fig. 4a. The desired response, the 14+ signal in Fig. 4a, appears as a result, as do several unwanted responses resulting, for example, from the 12th, 16th, and higher harmonics.

In the spectrum shown in Fig. 4a, the RF input consists of several signals from the frequency comb of a multiplier with outputs every 5.1 GHz. The unpreselected harmonic mixer shows several unwanted responses to each comb

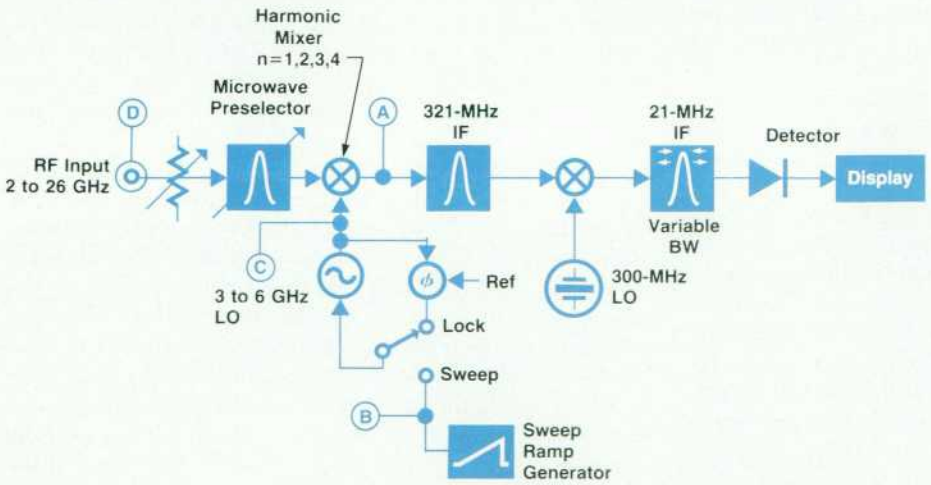


Fig. 2. *Microwave spectrum analyzer block diagram, showing interface points (A, B, C, D) with the millimeter-wave RF sections shown in Fig. 1.*

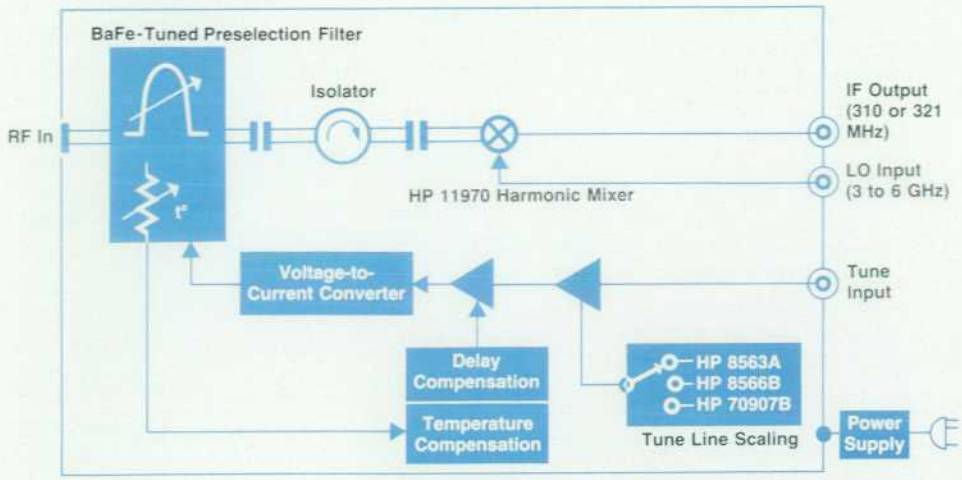
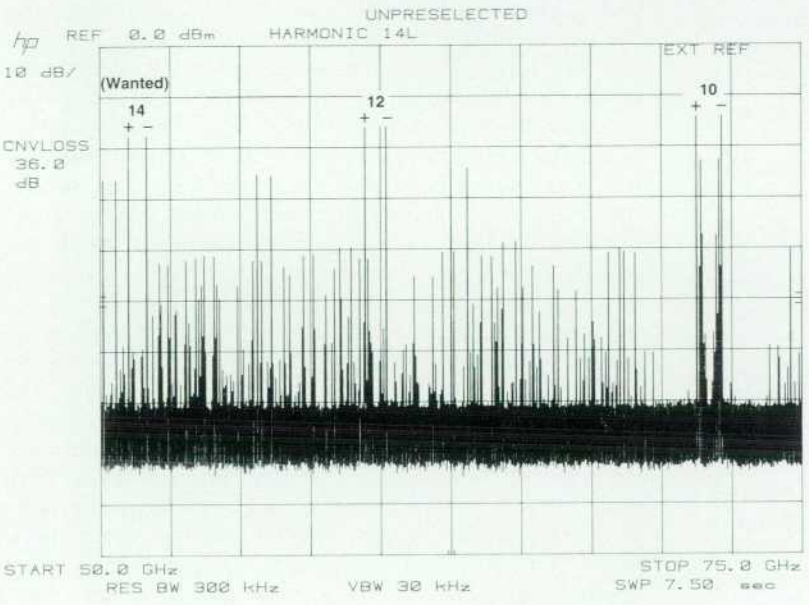
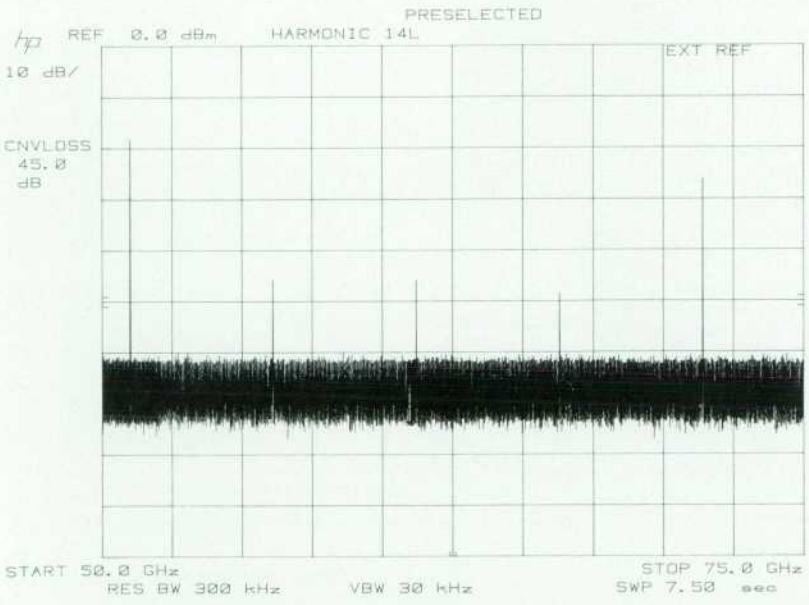


Fig. 3. *HP 11974 Series preselected millimeter-wave RF section block diagram.*



(a)



(b)

Fig. 4. *(a) An unpreselected spectrum analyzer sweep from 50 to 75 GHz for an input signal consisting of comb lines from a multiplier. There are several unwanted responses to each comb line. The harmonic responses to the 51-GHz comb line are labeled. (b) A preselected spectrum analyzer sweep for the same input signal. The multiple responses are eliminated and the multiplier comb lines every 5.1 GHz are clearly displayed.*

line, thereby producing many responses, most of which are unwanted and severely hamper measurements.

The HP 11974 preselected mixers add a waveguide tracking preselector to the harmonic mixer. The resulting V-band display is shown in Fig. 4b. Here, only one response occurs for each of the five comb lines.

Hexagonal Ferrite Filter Design

Having decided to design the HP 11974 Series by adding tunable bandpass filters as preselectors to the HP 11970 Series unpreselected harmonic mixers, we looked for the easiest way of doing things to make the best use of our resources. At the outset, we had decided to use doped hexagonal ferrite spheres as filter resonator elements. Their built-in frequency offset (see article, page 59) allowed us to employ existing YIG tuning magnet designs to cover waveguide bandwidths. Because the HP 11970 mixers have TE_{10} waveguide inputs, and because it seemed extremely difficult to reduce typical YIG filter loop coupling structures (Fig. 5) to the small sizes that would be required to make filters for the highest-frequency band (50 to 75 GHz), we decided to use TE_{10} waveguide as the transmission medium in our filter.

The high-frequency (53 to 80 GHz) barium ferrite filter work done by Lemke and Hoppe[3] served as a starting point for our filter design. Their two-sphere, iris-coupled filter used crossed input and output waveguides (Fig. 6) and produced RF magnetic fields in the two waveguides that were perpendicular to each other at the iris to reduce out-of-band leakage. A linear taper was used to reduce the height of the waveguide to allow a smaller gap between the magnet pole tips.

A two-sphere filter was built in U band (40 to 60 GHz) to demonstrate the feasibility of the crossed waveguide filter approach.[4] This filter had typical insertion loss of 4.5 dB, a 3-dB bandwidth of 325 MHz, and off-resonance isolation greater than 30 dB. The spheres were aligned on beryllia rods, which were slipped into holders that allowed ±0.1 mm of sphere adjustment from side to side and up and down in relation to the iris. The sphere rods were inserted through the reduced-height sidewall of the waveguide so that it was possible to center the spheres exactly over the iris and to move them closer together or farther apart to change the sphere-to-sphere coupling. In Fig. 7, the response of this filter is shown centered at approximately 48.5 GHz and moved up by 4.5 dB so the off-resonance isolation can be read easily off the plot.

The low-frequency side of the filter's response cuts off more quickly than the high-frequency side, and 650 MHz away from the peak of the passband the rejection is about

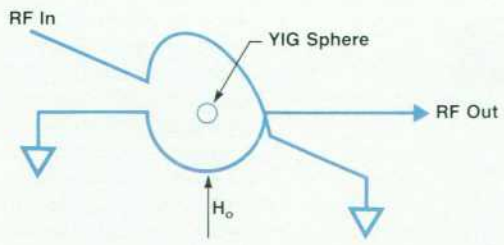


Fig. 5. *A single stage of a typical YIG filter.*

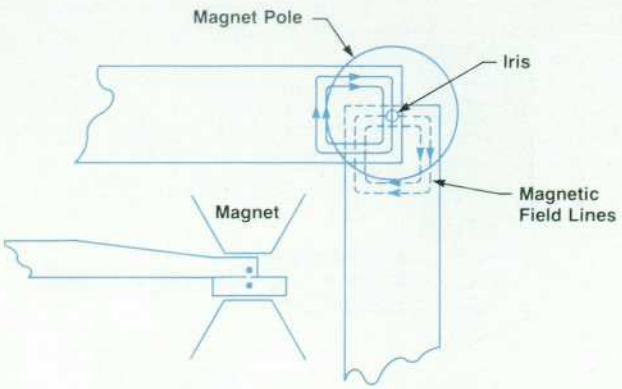


Fig. 6. *Two-sphere waveguide bandpass filter.*

35 dB. The rejection of a filter 650 MHz away from the peak is important for preselection applications because the IFs used in the HP instruments are approximately 310 MHz and 321 MHz. An unpreselected mixer will display an image signal at the same amplitude as the true signal at two times the IF away from the true signal. Therefore, much of a filter's usefulness depends on its image rejection, which is a measure of how much this unwanted trace is suppressed. By adjusting the spheres farther apart or closer together, and by changing the iris diameter and the sphere size, the best compromise between filter insertion loss, image rejection, and off-resonance isolation can be achieved.

Two-sphere filters were built in the other millimeter-wave bands using the information obtained from the U-band filter and applying appropriate scaling factors. The results for insertion loss and off-resonance isolation for the family of two-sphere waveguide filters[5] are shown in Figs. 8 and 9, respectively. The 3-dB bandwidths of these filters were 200 to 350 MHz. Although the insertion loss results were acceptable, the image rejection and off-resonance isolation of these filters were not sufficient for instrument applications. The goal was then changed to design a filter with off-resonance isolation and image rejection greater than 55 dB.

A literature search showed three-sphere and four-sphere

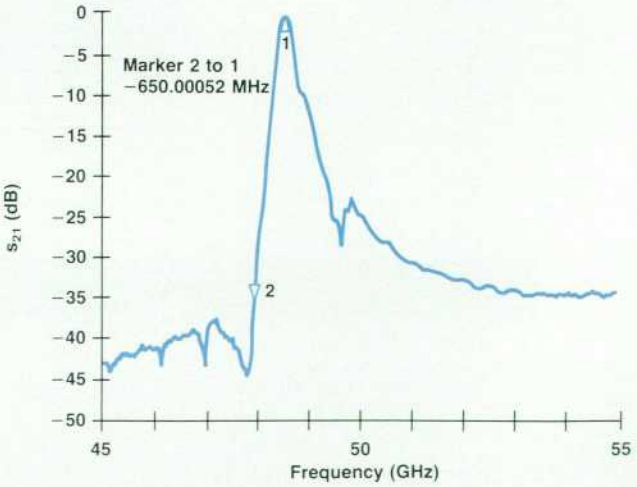


Fig. 7. *Two-sphere U-band filter response.*

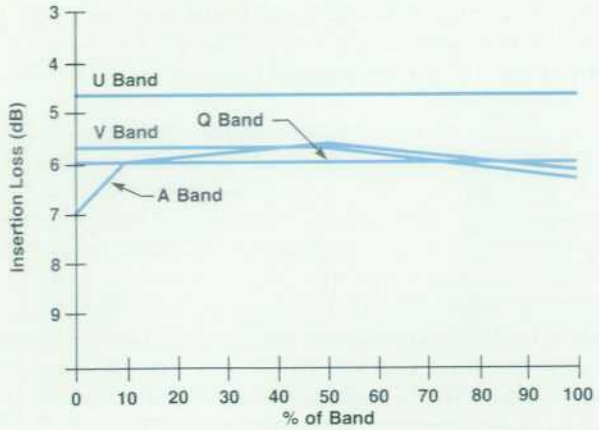


Fig. 8. *Insertion loss of two-sphere filters.*

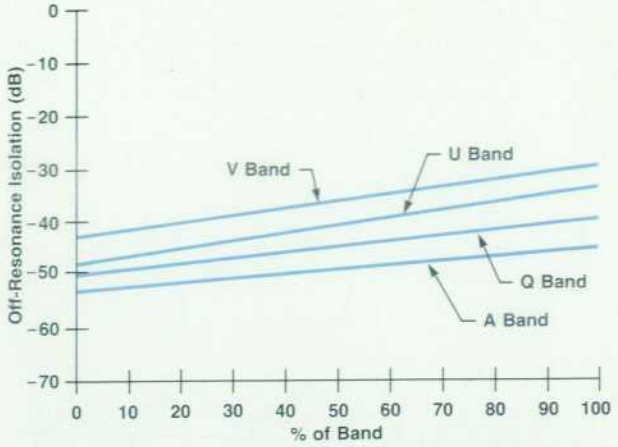


Fig. 9. *Off-resonance isolation of two-sphere filters.*

waveguide filter designs, but none of them would give the required off-resonance isolation at millimeter-wave frequencies. Our next design consisted of two of the above two-sphere filters under one set of magnet pole tips, connected by a very short transverse waveguide (Fig. 10). This four-sphere filter configuration does not increase the magnet pole tip separation, but in theory should double (in dB) the insertion loss, off-resonance isolation, and image rejection of the two-sphere filters previously built. To simplify the mechanical design, sphere mounts were machined from low-dielectric-constant plastic and epoxied over the irises. Resonator spheres were then placed on the sphere mounts, aligned and epoxied in place (Fig. 10). This sphere mounting technique allows accurate measurement of the sphere separation after mounting to determine sphere-to-sphere coupling.

The one significant difference that was expected in going to the four-sphere design was the possibility of the two irises and the short transverse guide (one wavelength long at approximately 80% of band) forming a coupled-cavity bandpass filter that might give a fixed-frequency spurious response. When the first four-sphere filters were turned on, they gave the expected double (in dB) off-resonance isolation, insertion loss, and image rejection, as well as the cavity-mode response (Fig. 11). By narrowing the width of the input and output waveguides and moving the spheres off-center towards the center of the filter, the one-wavelength cavity mode can be pushed 5 to 6 GHz above the top frequency in the band. The one-wavelength cavity mode can thus be eliminated by shortening the transverse guide. However, this brings the one-half-wavelength cavity mode in-band at about 15% of the band. The one-half-wavelength cavity mode is not as strong as the one-wavelength mode, and can be suppressed very well (Fig. 12) by introduction of a distributed loss in the transverse guide to detune the cavity. This loss is effected by a thin sheet of Kapton (plastic) between the sides of the transverse guide and the iris plate to allow some energy to leak out. The Kapton sheet is shown in Fig. 13, which also shows the four-sphere filter assembly.

Four-sphere filters using scandium-doped barium ferrites as resonators are presently being built in A, Q, U, and

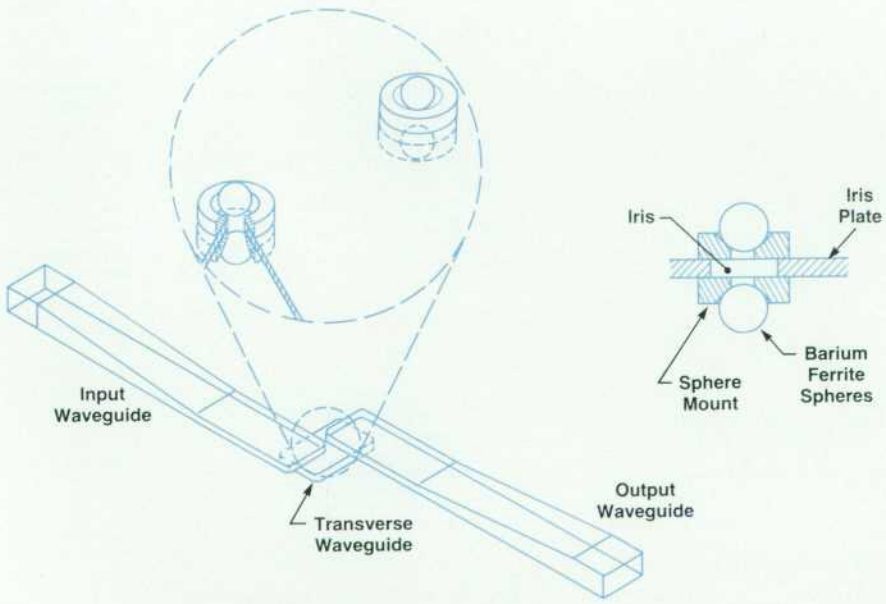


Fig. 10. *Four-sphere filter design.*

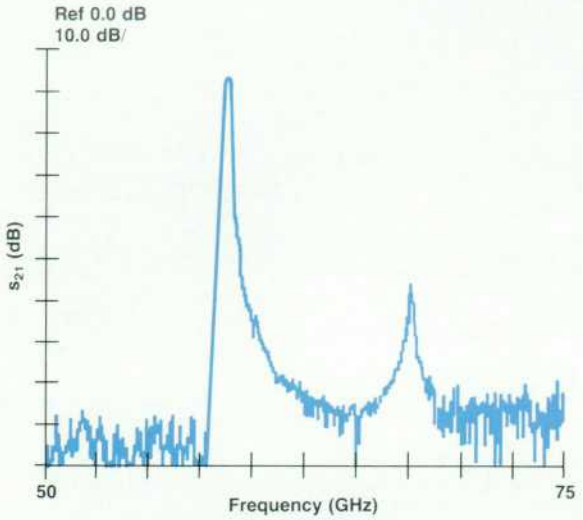


Fig. 11. *First four-sphere filter response shows cavity mode resonance.*

V bands. They typically have insertion loss of 8 to 12 dB, 3-dB bandwidth of 120 to 200 MHz, image rejection greater than 55 dB, and off-resonance isolation greater than 70 dB. These performance figures represent trade-offs that were made between the different parameters. For instance, by mounting the spheres closer together (top to bottom) a four-sphere V-band filter was made having 4 to 6 dB insertion loss across the band. Unfortunately, because of the tighter sphere-to-sphere coupling, the filter skirts were wider and the image rejection was degraded.

Filter Drive Circuitry

For proper system operation, the barium ferrite filter must track the input frequency of the spectrum analyzer. The HP 11974 Series preselected mixer receives a tune-ramp voltage from the spectrum analyzer that is proportional to the frequency of the spectrum analyzer's first local oscillator. For any given band, assuming a certain harmonic number, mixing sense, and mixer IF, this voltage is sufficient to determine the millimeter-wave frequency to which the spectrum analyzer is tuned. This voltage is then converted to a coil current that will tune the filter to the appropriate frequency.

To provide the correct current to the filter, the frequency-versus-coil current characteristics of the filter must be taken into account. The frequency of the barium ferrite filters varies linearly with current, and a straight-line approximation is sufficient. For example, a V-band filter typically deviates from a straight-line tuning equation by no more than ±90 MHz over the entire range from 50 to 75 GHz. Small tuning nonlinearities are compensated by using the preselector peak function of the spectrum analyzer. This function provides a small offset to the tune voltage to peak the filter on the signal being measured.

Because of the internal anisotropic field of the barium ferrite spheres, very little current is required to tune the filters to the lowest frequency of the band. For all four bands, from 26.5 GHz to 75 GHz, the coil current required at the lowest frequency is approximately 70 milliamperes. The filters then tune to higher frequencies at a rate of 60 to 70 GHz/ampere. As a result, the widest frequency bands require the most current. The A band, with a span of 13.5

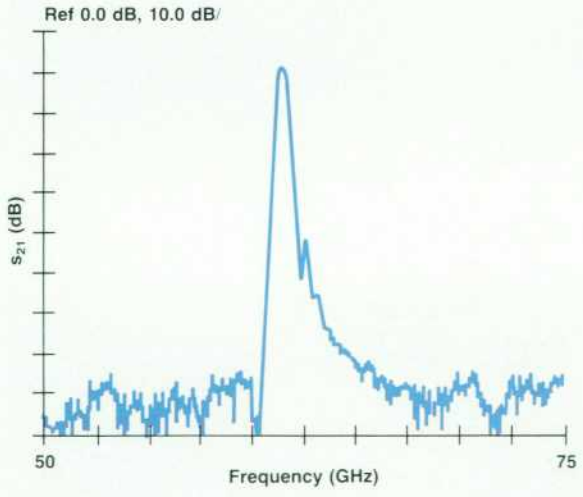


Fig. 12. *Four-sphere filter response with cavity mode suppression.*

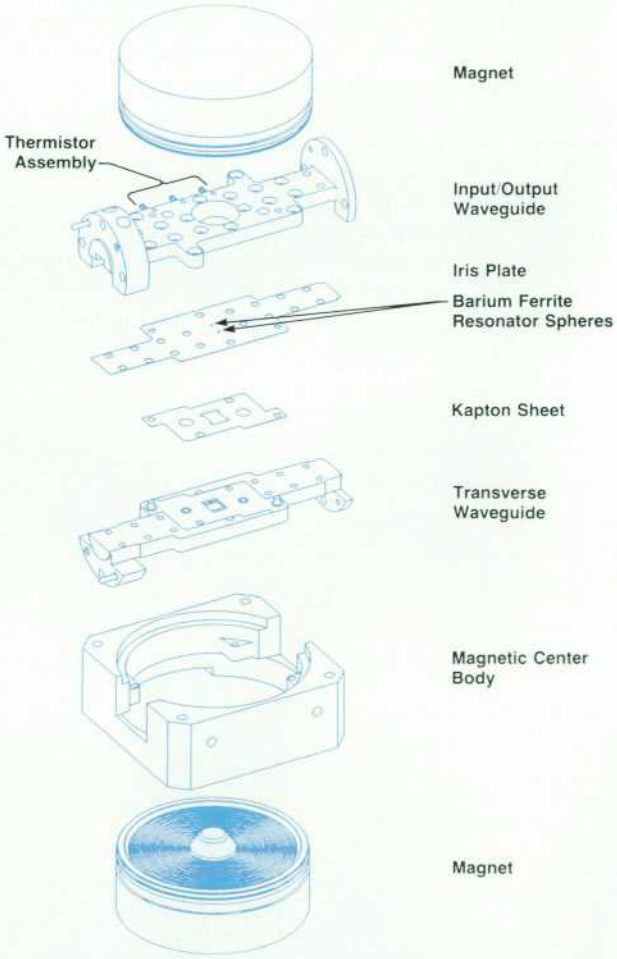


Fig. 13. *Four-sphere filter assembly.*

GHz, typically requires 270 milliamperes of coil current to tune to 40 GHz. V band, with a span of 25 GHz, typically requires 425 milliamperes of coil current to tune to 75 GHz. Coil current is provided by a 50-volt power supply. The coil current flows through the filter coil, a transistor that controls the amount of current flow, and a 3.1Ω resistor that is used to monitor the current flow, as shown in Fig. 14. To minimize the temperature dependent tracking errors, the 3.1Ω resistor has a low temperature coefficient, 5 ppm/°C, as do resistors in other critical locations. The power supply was chosen to be 50 volts to accommodate the voltage drops across all of the above items. The capacitor across the coil shunts unwanted high-frequency currents away from the coil. The Zener diode across the coil provides a discharge path for the coil at the end of a sweep, when the current through the transistor goes to zero.

The effect of temperature on the filter's frequency is another consideration in filter tuning. Some filters, such as the Q-band filter, have very little frequency drift with temperature, while others, such as the V-band filter, are very sensitive to temperature. With a constant coil current, a V-band filter drifts at a rate of +11.4 MHz/°C. For a temperature increase of 50°C, the center frequency of the filter would increase by nearly 600 MHz. Compensation for the temperature drift had to be considered because the 3-dB bandwidth of the filter is typically between 120 and 200 MHz, and this would mean that an input signal would no longer be within the passband of the filter.

Temperature and Delay Compensation

Temperature drift is compensated by monitoring the temperature at the filter and modifying the coil current. A thermistor network is used to monitor the temperature of the filter. The thermistor network consists of a thermistor composite composed of two thermistors encapsulated in epoxy and two linearizing resistors. The thermistor composite is located in the waveguide portion of the filter assembly (Fig. 13) and tracks the temperature at the barium ferrite filter. The network has a temperature dependent resistance that is linear from 0 to 100°C. The thermistor network is connected as the feedback portion of an amplifier that generates a voltage equivalent to the amount of filter frequency correction required. This voltage is then summed into the voltage that generates the filter coil current.

Although the temperature compensation required varies from band to band, the filters of each band are very consistent from unit to unit and across the frequency band. This consistency allows the correction to be based on temperature only. In the A and Q bands, the filter drifts lower in frequency with increasing temperature, while in the U and V bands, the filter drifts higher in frequency with increasing temperature.

Fig. 15 shows the frequency tracking errors of a V-band filter at 0°C, 25°C, and 75°C with no temperature compensation applied. The frequency tracking errors of the 25°C trace represent the deviations from a linear relationship between the filter coil current and the filter frequency. The spacing between the three traces represents the temperature drift of the filter with no temperature compensation applied.

Fig. 16 shows the frequency tracking errors of the same V-band filter with the temperature compensation circuitry enabled. The remaining frequency tracking errors fall within a range approximately equal to the 3-dB bandwidth of the filter. The preselector peak function of the spectrum analyzer removes these errors at a particular frequency.

In addition to temperature effects, compensation must be provided for the effect of filter tuning delay. When the spectrum analyzer sweeps at a fast rate, the filter, tuned by the current through a coil with inductance of about 0.8 henry, tends to lag behind. This effect is compensated by placing a differentiator in the HP 11974 tune voltage path.

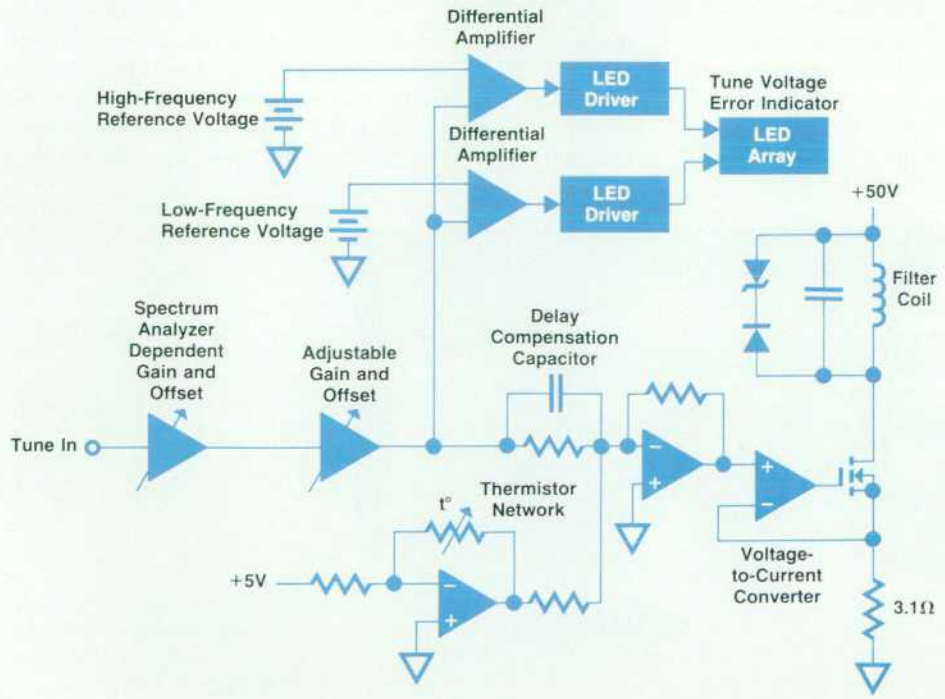


Fig. 14. *Simplified HP 11974 filter drive circuitry.*

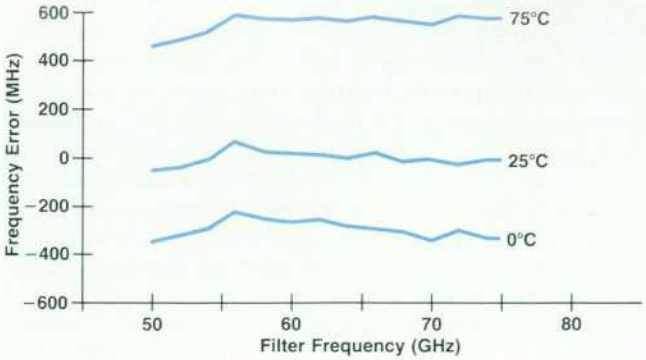


Fig. 15. *V-band filter tracking error without temperature compensation.*

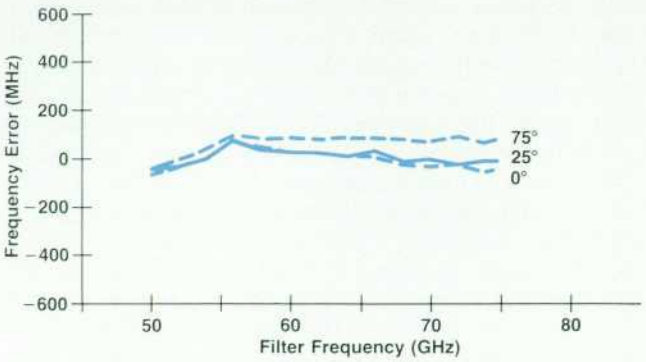


Fig. 16. *V-band filter tracking error with temperature compensation.*

At slow sweep rates, this circuit has no effect. At fast sweep rates, additional coil current is provided to help the filter keep up with the spectrum analyzer. With this compensation applied, the spectrum analyzer can be swept at a maximum sweep rate of 40 GHz/second.

Spectrum Analyzer Compatibility

The HP 11974 Series preselected mixers are designed to operate with three families of Hewlett-Packard spectrum analyzers: the HP 70000 modular spectrum analyzer family with the HP 70907B external mixer interface module, the rugged, portable spectrum analyzer family including the HP 8560A, HP 8561B, HP 8562A, and HP 8563A, and the HP 8566B, a high-performance R&D bench spectrum analyzer. Fig 17 shows the HP 11974 Series and the spectrum analyzers. Older models of these spectrum analyzer families can be made compatible by installing a retrofit kit.

To be compatible with the HP 11974, the spectrum analyzer must meet certain requirements. First, the spectrum analyzer must have a first LO frequency range of 3 to 6 GHz at the proper power level. The nominal power level of the first LO output is +14.5 dBm to +16 dBm. Second, the first IF of the spectrum analyzer must be compatible with the HP 11974. Each spectrum analyzer mentioned above has a first IF of either 310.7 MHz or 321.4 MHz. Finally, the spectrum analyzer must provide a voltage output that is proportional to the frequency of the first LO of the spectrum analyzer. Each of the three spectrum analyzer families has a different definition for the tuning voltage provided. Because of this, the HP 11974 has switches that are used to identify the spectrum analyzer with which it is to be used. For each switch setting, a specific gain and offset are applied to the tune voltage so that the filter will be properly tuned.

Another requirement for the tune voltage of the spectrum analyzer is that it have a variable offset summed in. The correct amount of offset to apply at any given frequency is determined by the preselector peak function.

Before operating the HP 11974 with the spectrum analyzer for the first time, two potentiometer adjustments must be made. These adjustments match the tuning voltages provided by the spectrum analyzer to the reference voltages in the HP 11974. After these adjustments are made, the preselector filter will track very well the input frequency of the spectrum analyzer. The preselector peak function is used to eliminate the remaining frequency tracking errors at any given frequency. When executed, this function causes the spectrum analyzer to vary its tune voltage to the HP 11974 and monitor the signal level of the marked response on the screen. At the maximum response level, the filter has been peaked. The frequency range of the preselector peak function is proportional to the harmonic number on which the mixer operates. For most of the analyzers, the preselector peak range is ±260 MHz in

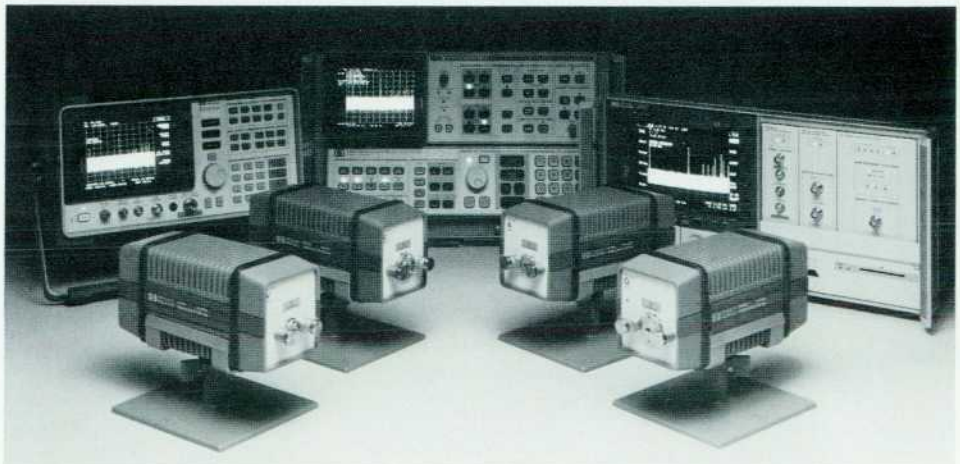
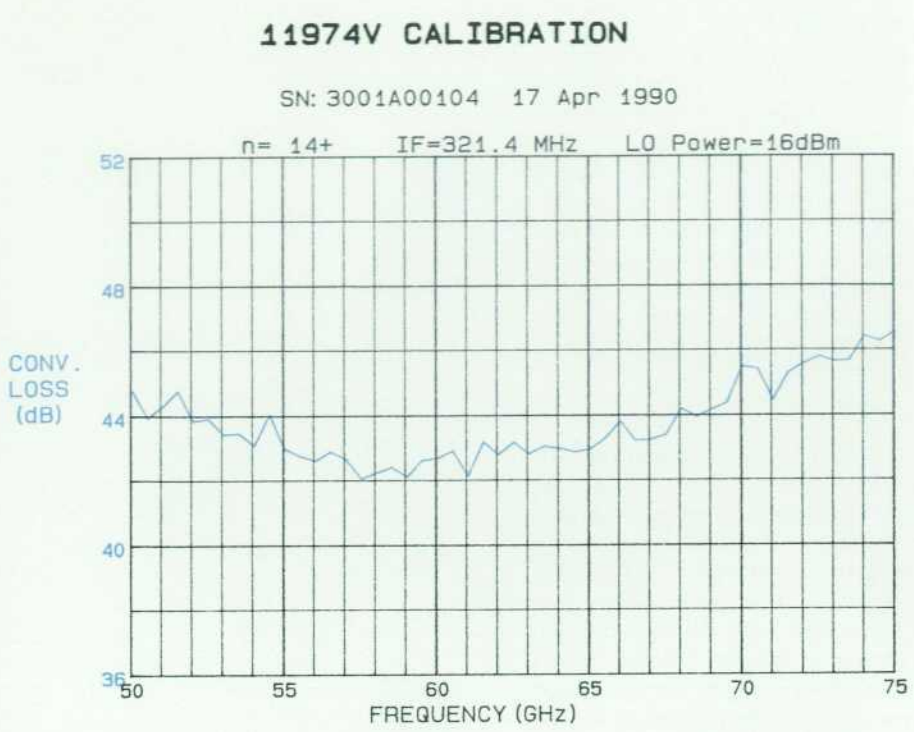


Fig. 17. *HP 11974A/Q/U/V preselected millimeter-wave RF sections with mainframe microwave spectrum analyzers (HP 8563A, HP 8566B, HP 70000).*



FREQ.	CONV. LOSS	FREQ.	CONV. LOSS	FREQ.	CONV. LOSS
50.00	44.90	58.50	42.54	67.00	43.37
50.50	44.08	59.00	42.25	67.50	43.51
51.00	44.44	59.50	42.74	68.00	44.31
51.50	44.90	60.00	42.81	68.50	44.05
52.00	43.97	60.50	43.03	69.00	44.28
52.50	44.04	61.00	42.27	69.50	44.49
53.00	43.56	61.50	43.30	70.00	45.61
53.50	43.59	62.00	42.92	70.50	45.53
54.00	43.22	62.50	43.29	71.00	44.57
54.50	44.16	63.00	42.93	71.50	45.40
55.00	43.11	63.50	43.16	72.00	45.68
55.50	42.88	64.00	43.09	72.50	45.91
56.00	42.74	64.50	42.98	73.00	45.76
56.50	43.02	65.00	43.07	73.50	45.78
57.00	42.79	65.50	43.40	74.00	46.53
57.50	42.18	66.00	43.92	74.50	46.38
58.00	42.37	66.50	43.33	75.00	46.66

Fig. 18. *Conversion loss calibration chart is supplied with each RF section. The data is entered into the mainframe spectrum analyzer.*

A band and ±450 MHz in V band.

Conversion loss data for each instrument is required to make accurate amplitude measurements. Each HP 11974 is shipped with a graph and a tabular listing of its conversion loss as a function of frequency, as shown in Fig. 18. The conversion loss measurements are traceable to the United States National Institute of Standards and Technology. Data from the conversion loss table can be entered into the spectrum analyzer so that amplitude readings will automatically be referenced to the input of the HP 11974. In addition to the conversion loss table and graph, a conversion loss label is permanently attached to the HP 11974 for reference.

Acknowledgments

R&D team member Dick Beardsley designed all the critical mechanical parts and made them look simple. He also organized the R&D retreats at the salmon school locations off the Northern California coast. The product introduction team completed their work in record time and included Robert Charlton, George Zimenski, Ron Flatt, Mariko Hoy, Lonnie White, Jim Lusk, Tom Berto, Joe Wax, Rich Pope, Bob Fullmer, Dennis DeMaria, Rebbie Toledo, Karen Bigham, Mike Picha, Bernie Hoven, Joyce Wong, Dennie Yamaoko, and Kathy Sparks. Mike Dethlefsen, Ernie deMartini, Mike Brown, and Steve Flint designed the retrofit kits vital to the project. Marketing efforts were by Eric Brown and Dennis Handlon. Important early development work on the filter and test routines was performed by Jimmie Yarnel, Dennis Derickson, Matt Fowler, and Hiroshi Imiazumi. Summer intern Davie Zoneraich built the first version of the millimeter tracking generator test set. Our lab section management, Frank Angelo and Toni Coon, endured endless project reviews and kept us inspired. And then there is Frank David, who peeled the company's first layer from the millimeter onion a decade ago.

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Hexagonal Ferrites for Millimeter-Wave Applications

Scandium-doped, M-phase barium ferrite has the necessary properties. Crystals are grown and spheres are processed and tested in-house.

by Dean B. Nicholson

Ferrite spheres are commonly used as resonator elements in magnetically tunable bandpass filters. At frequencies below approximately 30 GHz, yttrium iron garnet spheres (abbreviated YIG, chemical formula $Y_3Fe_5O_{12}$) are used extensively in this role. At frequencies above about 30 GHz (the millimeter-wave region) problems become apparent with the magnetic components used to tune the YIG spheres. These problems include electromagnet heating, tuning nonlinearities, and hysteresis.

The tuning equation of a YIG sphere,[1] applicable with H_a parallel to H_o, is:

$$f_{resonance} = (2.8\ MHz/Oe)(H_o + H_a), \qquad (1)$$

where H_o is the applied dc magnetic field and H_a is the internal anisotropy field (70 Oe for YIG). Using this equation, the maximum usable frequency of a YIG sphere can be calculated to be about 64 GHz, assuming that the material used in the tuning magnet pole tip has the highest saturation flux density available (approximately 23 kilogauss for a cobalt-iron alloy).[2] The anisotropy field H_a can be thought of as a built-in magnetic field that acts along a crystal axis, or in some cases a crystal plane. When the anisotropy field is parallel to the applied field, it gives a frequency offset that reduces the applied dc magnetic field needed for resonance at a given frequency.

It was obvious that a new resonator material would be required to make tunable bandpass filters to serve as preselectors for the HP 11970 Series harmonic mixers covering from A band (26.5 to 40 GHz) up to V band (50 to 75 GHz). Using equation 1, it can be seen that if ferrite materials similar to YIG but with higher H_a could be found, then it would be possible to build magnetically tunable bandpass filters that cover waveguide bands in the millimeter-wave region using moderate magnetic tuning fields (Fig. 1). A class of material with this property is the hexagonal ferrites.[3]

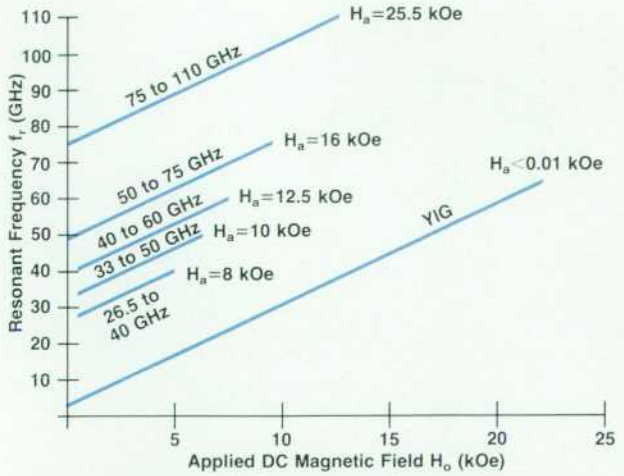

Fig. 1. *Ferrite resonance frequency as a function of dc magnetic field for various values of the anisotropy field.*

Properties of Hexagonal Ferrites

Hexagonal ferrites are so named because this class of materials has a hexagonal crystal lattice, which produces crystals that have distinctly hexagonal shapes (Fig. 2). The hexagonal ferrites have a large number of phases. Fig. 3 compares the parameters of the most important phases (there are many more!) to YIG parameters.[4,5,6,7,8] The most useful hexagonal ferrites have a property called uniaxial anisotropy (Fig. 4), which means that the anisotropy field lies along only one axis, which is the C axis for the hexagonal crystal. Hexagonal ferrites are commonly referred to by their phase and composition. For example, M-phase barium ferrite is $BaFe_{12}O_{19}$.

The minimum useful frequencies listed in Fig. 3 come from three constraints. First, with the anisotropy field aligned with the applied field, equation 1 shows that the lowest frequency of resonance is (2.8 MHz/Oe)(H_a) with negligible applied field. Second, the magnetic dipoles in

Fig. 2. *Hexagonal ferrite crystals.*

Material		$4\pi M_s$ (Gauss)	H_a (Oe)	Q_u	Frequency of Q_u Measurement (GHz)	Minimum Useful Frequency (GHz)	Temperature Dependence of Resonant Frequency (MHz/°C)	Curie Temp. (°C)
YIG	$Y_3Fe_5O_{12}$	1,800	70	9,500	9	3.4	Can be made 0 to first order by sphere alignment	277
GaYIG	$Y_3Fe_4Ga_1O_{12}$	400	50	1,500	9	0.75		167
Hexagonal Ferrites								
M-phase	$BaFe_{12}O_{19}$	4,800	17,000	950	63	52	+15	450
M-phase	$BaFe_{11.1}Sc_{.9}O_{19}$	3,800	8,000	430	39	26	~0	340
M-phase	$SrFe_{12}O_{19}$	4,700	18,700	950	62	57	+16	460
M-Phase	$SrFe_{10.5}Al_{1.5}O_{19}$	3,300	25,500	670	81	75	+25	410
Y-phase	$Ba_2Zn_2Fe_{12}O_{22}$	2,850	9,900	1,250	17	9	---	101
U-phase	$Ba_2Zn_2Fe_{36}O_{60}$	3,890	9,300	500	26	30	---	400
Z-phase	$Ba_3Zn_2Fe_{24}O_{41}$	3,900	4,800	310	35	17	---	360

Notes: 1. Sc and Al dopings can be varied continuously.

2. Y phase has planar anisotropy. $f_r = (2.8\ MHz/Oe)(H_o(H_o+H_a))^{1/2}$ when the anisotropy plane is aligned with both dc and RF fields.

Fig. 3. *Summary of hexagonal ferrite and YIG parameters.*

a ferrite sphere with the applied magnetic field aligned with H_a will not all line up or "saturate" until a field of at least $4\pi M_s/3$ has been applied. Third, for very high-Q_u (unloaded Q) ferrites at low frequencies, such as YIG, with fields between one and two times $4\pi M_s/3$, the effect known as coincidence limiting[8] limits the amount of power that a ferrite device can handle to much less than 0 dBm. Therefore, YIG spheres are generally used with applied fields above two times $4\pi M_s/3$. For hexagonal-ferrite-sphere-tuned devices, this power-limiting effect has not been seen at power levels up to 20 dBm for our bandpass filter configurations and thus should not present a problem for this application.

As Fig. 5 shows, scandium and aluminum dopings can be varied arbitrarily in M-phase hexagonal ferrites to give the desired H_a.[4] The scandium-doped M-phase barium ferrite will satisfy the frequency range requirements at the lower frequencies while the aluminum-doped M-phase strontium ferrite will satisfy the requirements at the higher frequencies. Although it is possible to dope M-phase barium ferrite with aluminum to raise its resonant frequency and dope M-phase strontium ferrite with scandium to lower its resonant frequency, in general, the higher the doping level the more the Q_u of the resonator is degraded. Therefore, dopants and materials are chosen so that the least amount of dopant is used to cover a given frequency range.

Other desirable properties of M-phase hexagonal ferrites are that they have high $4\pi M_s/3$ for good coupling to the RF fields, high Curie temperatures for low sensitivity to temperature change, and fairly high Q_u.

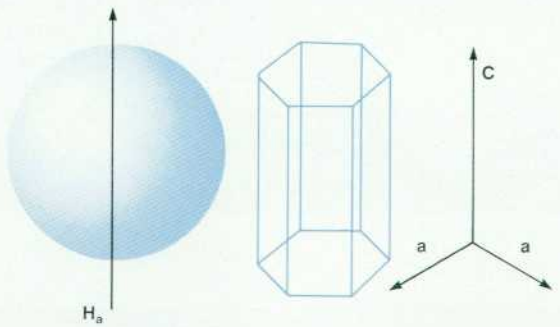

Fig. 4. *Uniaxial anisotropy in hexagonal ferrites.*

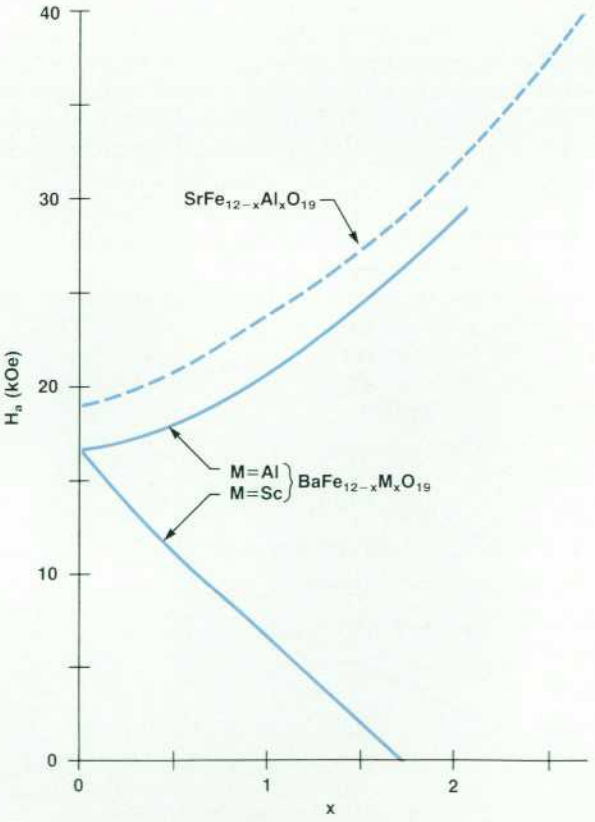

Fig. 5. *Anisotropy field changes with doping. Adapted with permission from reference 4.*

Sphere Production and Test

Once the selection of the M-phase hexagonal ferrites was made and it was found that crystals were unavailable commercially, a crystal growth program was begun at the HP Microwave Technology Division. In the literature, hexagonal ferrite crystals are typically grown from a BaO/B_2O_3 flux using slow cooling. We used a slow cooling furnace with multiple small crucibles per run and free nucleation (no seed crystals) for quick optimization of charge composition and temperature profiles. Now that growth conditions have been optimized, a single larger crucible is used for each growth run with a larger charge so that larger crystals can be grown. The total volume of liquid charge in the crucible at the start of crystal growth is approximately 320 ml. The total weight of crystals obtained from the growth is about 70 grams.

The processing of hexagonal ferrites to spheres is conceptually very similar to YIG sphere processing. Because of the brittle nature of hexagonal ferrites, proprietary grinding and polishing techniques had to be developed to avoid chipping the sphere poles. In addition, a separate sphere testing system was developed to test the Q_u of the hexagonal ferrite spheres, which must be tested at the millimeter wave frequencies at which they will be used.

Summary

Because of their high magnetic anisotropy fields, spheres made of suitably doped M-phase hexagonal ferrites were chosen as resonator elements in magnetically tunable bandpass filters. These bandpass filters cover waveguide bands above 26.5 GHz and are used as preselectors in the HP 11974 Series of millimeter preselected RF sections. When no outside supplier of hexagonal ferrite spheres could be found, crystal growth and sphere processing and test capabilities were developed in-house.

Acknowledgments

I would like to acknowledge Frank Gary for developing the sphere grinding and polishing processes and assisting with crystal growth. Without his help the project would have been immeasurably more difficult. In addition, I would like to thank Jerry Gladstone for management support even when the success of the project seemed uncertain at best.

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HP DIS: A Development Tool for Factory-Floor Device Interfaces

The HP Device Interface System provides a development facility that includes a high-level Protocol Specification Language, a testing facility, and a run-time facility for device interfaces that run in an HP-UX environment on HP 9000 computers.

by Kent L. Garliepp, Irene Skupniewicz, John U. Frolich, and Kathleen A. Fulton

EFFICIENT DEVELOPMENT OF INTERFACES between computers and factory-floor devices can be a serious challenge in factory automation projects.[1] These factory-floor devices consist of programmable logic controllers (PLCs), robots, numerically controlled machines, gauges, scales, and other devices. The problem is that they may come from many manufacturers and may have different, proprietary interfaces.

For a few major brands of programmable controllers, there are off-the-shelf communications packages that can be purchased. This solution has limited applicability if the needs vary from what is implemented in the package.

If flexibility is needed, a customized interface can be written. At present, development of specific device interfaces is a time-consuming, exacting, and expensive process requiring a fairly high level of expertise. The process generally consists of characterizing the device's communication protocol and then writing, changing, or enhancing programs, subroutines, and test suites. This process is well-known to all interface developers and creates a slow response to market needs.

In the long run, the use of communications standards, such as the Manufacturing Automation Protocol[2] (MAP), will eliminate many of the device connectivity problems and the response to market needs will improve significantly. In the meantime, many factory-floor devices exist and have long useful lives remaining. Many are simple devices, such as gauges with simple interfaces, that may never conform to a standard.

To reduce the cost of developing customized interfaces for devices that need them and to shorten the time required for such efforts, tools are needed to simplify the development and testing of the interfaces. This is the objective of the HP Device Interface System (HP DIS). HP DIS is a toolset that helps developers create and test interfaces between computer applications and RS-232-compatible factory-floor devices in less time than before. The resulting interfaces run in an HP-UX environment on HP 9000 Series 300 or 800 computers.

HP DIS offers three facilities to make the development and implementation of device interfaces more efficient. A development facility provides a high-level Protocol Specification Language[3] for defining the communications logic. A testing facility provides a test generator, a test exerciser, and a device simulator. A run-time facility executes the protocol in real time. Fig. 1 shows a typical protocol development cycle and the use of the HP DIS toolset.

HP DIS: the Tools Approach

A diagram of the HP DIS system is shown in Fig. 2. The three bubbles correspond to the above-mentioned three facilities provided by HP DIS. These allow the system developer to develop, test, and run device interfaces.

The development facility is simply a compiler that generates a *protocol interface*. The protocol interface is an executable process that forms the central component of an

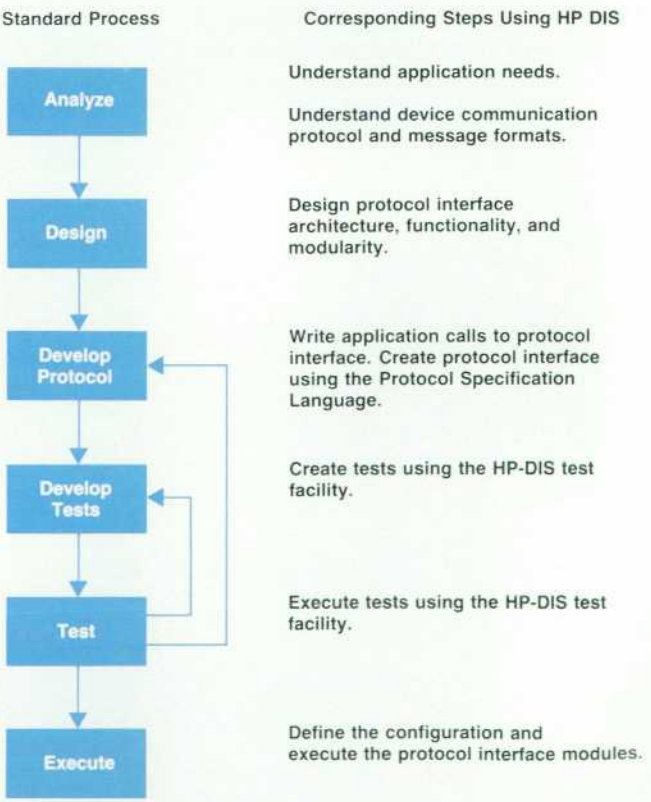

Fig. 1. *The process of creating a device interface.*

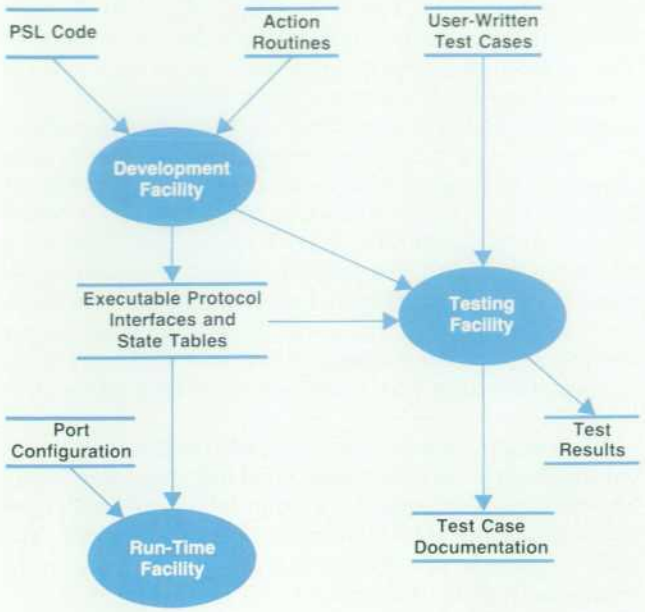

Fig. 2. *HP DIS facilities.*

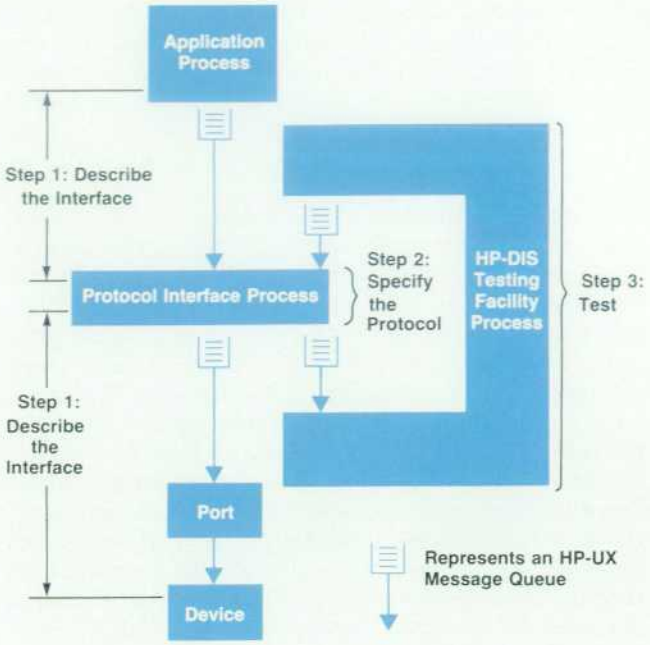

Fig. 4. *Steps in protocol interface development using HP DIS.*

HP DIS system. The input to the compiler is a description of the device protocol, written in Protocol Specification Language (PSL). PSL allows the user to describe a state graph and its associated state table in a high-level format (see "Finite State Machine," page 65).

Other inputs to the development facility are subroutines that can be linked to the protocol interface. In HP DIS these are called *action routines* (see "Action Routines," page 69).

The run-time facility provides the execution environment for the protocol interfaces. When the protocol interface runs, it communicates with ports, other protocol interfaces, and other C programs through HP-UX message queues. Using a description of the protocol interface's associated I/O ports, the run-time facility manages the ports, message queues, process startup, and process shutdown.

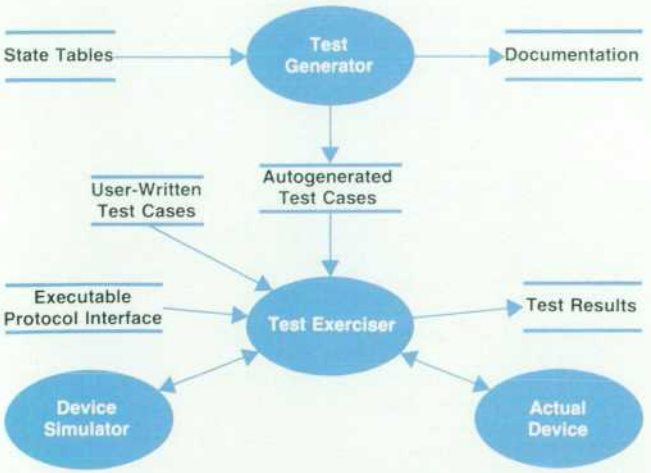

Fig. 3. *HP DIS testing facility.*

The development and run-time facilities also provide the following features:

- A contributed library of example protocol interfaces, tutorial protocol interfaces, and other helpful tools
- The ability to implement user-defined lookup tables
- Eight-bit native language support
- Access between multiple devices and multiple interfaces
- The ability to add and delete protocol interfaces dynamically in a running system.

A diagram of the HP DIS testing facility is shown in Fig. 3. This facility consists of a test generator and a test exerciser.

The test generator takes the state table and creates test cases. The test cases are fed to the test exerciser, which executes each test case by sending messages to the protocol interface under test. The test exerciser attempts to achieve each state listed in the state table, for up to 100% coverage.

Optional inputs to the test exerciser are user-written test cases. The test exerciser executes a sequence of test cases and compares expected results to the results of the protocol interface under test. Actual devices or I/O ports are not necessary for testing; factory-floor devices can be simulated by describing their messages.

The output of the testing facility includes test case documentation and test results. The testing facility also provides the following features:

- Full or partial data tracing
- Either menu-driven execution or script execution of test cases
- Protocol filters to simulate garbled messages, time-outs, and expression matching
- Notification of percentage covered.

An HP DIS Example

There are three steps in developing an interface (see Fig. 4). The first step is to describe the interaction between the application and the factory-floor device interface. The second step is to specify the device protocol in a language that HP DIS can compile. The third step after successful compilation is to generate the test scripts and test the logic of the developed interface. These steps are illustrated by the following example.

Describing the Interface. A block diagram of the system interfaces for this example is shown in Fig. 5. The interface between the application and the device interface is an HP-UX message queue. Read and write subroutines are available for the application program developer to send buffers to the device interface and receive buffers from it. These subroutines allow referencing either the HP-UX message queue name or the device application name. The links between the HP-UX message queues and the device interface are established by the run-time facility through a configuration file (Fig. 6). The configuration file is used by the run-time facility to establish the queues, start the defined interfaces, create the links, and configure the ports from the port definitions. The configuration process eliminates the need for a detailed understanding of HP-UX interprocess communication and RS-232 serial port initialization.

The buffers passed through the queues must be designed to carry the information needed by the device interface. The device interface can require the application to pass device-specific data directly or can translate generic functions into device-specific data. Device interfaces can range from very device dependent to completely device independent. In the latter case more logic will be required in the device interface.

For the sake of simplicity, this example uses the device dependent approach. The application outbound buffer contains a six-byte header and a variable-length data string. The application inbound buffer contains a status byte and a variable-length data string.

Specifying the Protocol. One of the methods of specifying the protocol is a transition diagram translated into a state diagram. This is particularly convenient for translating the protocol into a language HP DIS can compile. Figs. 7a and 7b describe a transition diagram and a state diagram for a nontrivial protocol. This example protocol is based on the Allen-Bradley Data Highway I protocol, but only exemplifies the major features. This example assumes synchronous communication. No new request is sent from the computer to the factory-floor device until a previous request is satisfied.

The computer sends a message (MSG) to the device (Fig. 7a) and waits for an acknowledgment from the device (ACK). The computer then waits for a reply message (Fig. 7b). Each message consists of block control characters, a header, and data. In the case of a read request, the data field from the computer contains the address and the length of the request. The reply data from the device consists of the values requested. In the case of a write request, the data field from the computer contains the address and the values for the request. The reply data from the device consists of an internal status for the request.

In the event of a communication failure, either the computer or the device can reply with a failure message (NAK). The protocol interface must also recognize that no response (TO) is a failure. Other failure mechanisms are not taken into account in this example.

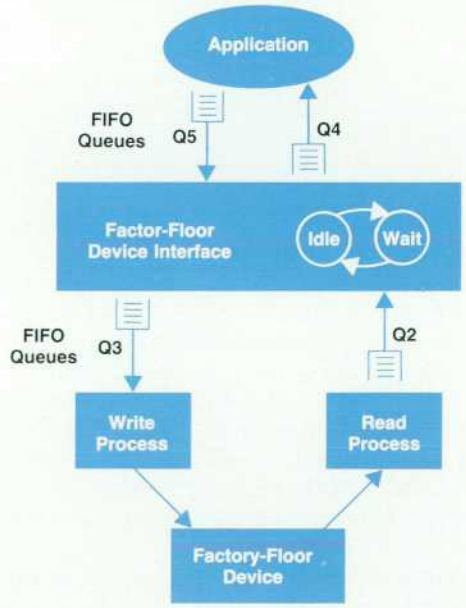

Fig. 5. *System interfaces for HP DIS example. The queues are HP-UX message queues.*

```
PI_DEFINITIONS

  Runtime_Name        = Device_xx;
  Runtime_File_Name   = /users/test/Device_xx;
  Runtime_Type        = P;
  Runtime_Priority    = 51;
  Port_Name           = AB;

PORT_DEFINITIONS

  Port_Name           = AB;
  Port_Major_#        = 1;
  Port_Minor_#        = 4;
  Baud_Rate           = 9600;
  Character_Size      = 8;
  Parity              = N;
  Stop_Bits           = 1;
  Read_Type           = BCC_AB;
  Output_Queue        = Q2;
  Input_Queue         = Q3(Device_xx);

QUEUE_DEFINITIONS

  Queue_Name          = Q2,Q3,Q4,Q5;

  Queue_Link
  Q5 > Device_xx;
  Device_xx > Q3;
  Q4> Device_xx;
  Device_xx< Q2;
```

Fig. 6. *Device interface configuration file.*

Finite State Machine

The finite state machine model has been used in such diverse disciplines as computer design, neurophysiology, linguistics, automata theory, and communications.[1] The finite state machine model is a natural way to describe systems that process signals. This model is particularly convenient for specifying how messages are processed in device protocols.

Two standard representations used to describe a particular finite state machine are the state table and the state diagram.[2] A state table uses one row for each state and one column for each input. In each box are written the next state and the output. The first row of the state table is usually assigned to the initial state of the machine.

A state diagram is a directed graph in which each arc is labeled with the input that causes the transition and the output that is generated when the transition is triggered.

A classic example is a parity checker. This machine takes an input stream of bits of ones and zeros. For each input bit the machine produces an output indicating whether the entire input sequence so far has even or odd parity. The state table and diagram are shown in Fig. 1.

The HP DIS state table, written in PSL, is shown below. The initial, or home, state is have_even. When an event is triggered by the receipt of a 0 or 1, the protocol interface prints a message using the user action routine called U1.

```
Events
    zero_recd : response : 0;
    one_recd : response : 1;

States
    have_even : Home;

State_Table
    have_even : zero_recd :
      U1("print even")
      : have_even;

    have_even : one_recd :
      U1("print odd")
      : have_odd;

    have_odd : zero_recd :
      U1("print odd")
      : have_odd;

    have_odd : one_recd :
      U1("print even")
      : have_even;
```

State Table

	zero_recd	one_recd
have_even	have_even, "print even"	have_odd, "print odd"
have_odd	have_odd, "print odd"	have_even, "print even"

State Diagram

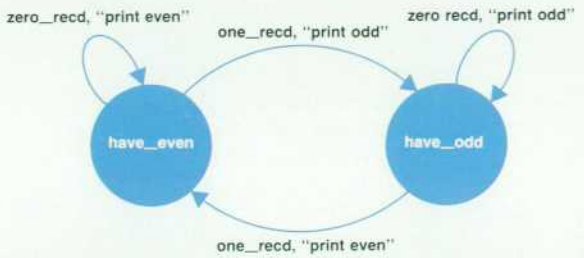

Fig. 1. *State table and state diagram for a parity checker.*

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Figs. 7a and 7b show state diagrams derived from the transition diagrams. The states and events form the logic of the protocol interface. Actions (or functions) are performed at each state-event pair. Fig. 7a also shows an event (retry exceeded) that is not supported by the transition diagram. This event is added to prevent endless looping.

A message from the device to the computer (Fig. 7b) will cause a reply message event, which would normally return directly to the IDLE state. This example will check the integrity of the byte stream by checking the BCC (block control character) count and branching to an extra state (CHECK). If the BCC count was incorrect, the original message will be sent back to the device. If the BCC count was correct the message from the device will be returned to the application. The combination of the IDLE state and the reply message event is included in case the device sends a message after time-out processing. If this were not included, the wrong message would be extracted from the HP-UX message queue during the next transaction. The message from the device is simply acknowledged and ignored.

Table I
Actions List

State	Event	Actions	Next
IDLE	Send message	Read message from application Build outgoing buffer from incoming buffer. Send message to device. Clear retry count. Increment message number. Start timer.	WAIT
IDLE	Reply message	Read message from device. Send acknowledgment (ACK) to device.	IDLE
WAIT	ACK	Stop timer. Read message from device. Start timer.	WAIT
WAIT	NAK	Stop timer. Read message from device. Resend message to device. Increment retry count. Start timer.	WAIT
WAIT	Reply message	Stop timer. Read message from device. Check block control character (BCC)	CHECK
WAIT	Time-out	Stop timer. Send no response message to application.	WAIT
WAIT	Retry exceeded	Stop timer. Send communications error message to application.	IDLE
CHECK	Message OK	Send acknowledgment (ACK) to device. Send reply data to application.	IDLE
CHECK	Message not OK	Send acknowledgment (NAK) to device. Increment retry count. Set timer.	WAIT

The state diagrams of Figs. 7a and 7b are combined into one state diagram in Fig. 8.

The actions to be performed at each state transition are listed in Table I. With some additional declarations this table can be transformed into a Protocol Specification Language (PSL) program that can be compiled. Previous decisions about the form of the messages from the application can be incorporated into the data structures.

Fig. 9 shows the PSL program ready for compiling and testing. The compiler not only checks the program syntax, but also tests the reachability of all states from/to the home (IDLE) state. This check ensures that there are no incomplete paths.

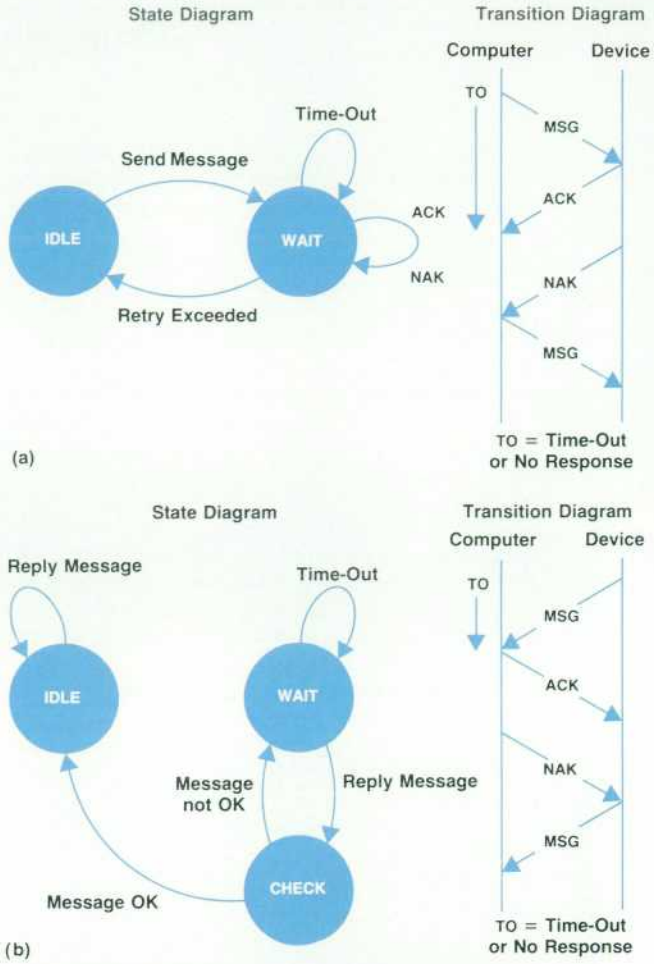

Fig. 7. *Transition and state diagrams for a nontrivial protocol. (a) Message from computer to device. (b) Message from device to computer.*

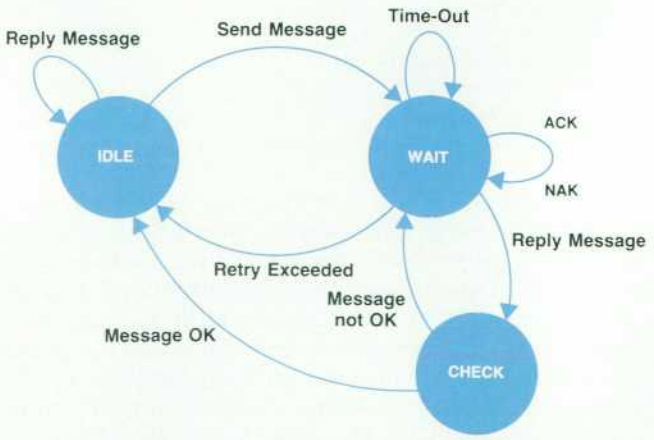

Fig. 8. *Protocol state machine state diagram obtained by combining Figs. 7a and 7b.*

Matching Messages

One of the most powerful features of HP DIS is the matching process. It is used for three purposes: for determining whether a message matches a request event or a response event, for parsing a message into a structure, and for delimiting streams of characters from a port. Each use is slightly different from the others, but they all have the same matching characteristics.

Through the PSL struct description, the user defines the fields in a structure that are to be matched. All variables describe a length of data. When a structure contains a variable, the data from the message is placed into the structure according to the length of the variable. Byte and Boolean variables are one byte long. Integer variables are two bytes long, and real and long variables are four bytes long. String variables can be NULL or up to 4K bytes long. Data from the message is parsed into the structure's fields according to the variable lengths.

Constants and literals are matched exactly. The lengths of data types are the same as above, but the message data must contain the bit pattern that matches the constant. Constants or literals adjacent to string variables are used for delimiting the strings.

The HP DIS compiler builds a table for each structure describing data in each field. The matching process then walks this table for each structure. If there are no string variables in a structure, then each byte is easily assigned to a structure field. There is no ambiguity. However, if there are any string variables in the structure, then ambiguity branching begins, because string variables can be NULL or up to 4K bytes long. The matching process branches, assigning this byte to both the string variable and to the next field. This ambiguity is resolved either by the next constant or by the end of the message.

HP DIS makes the first shortest match, unlike the HP-UX editor vi, which makes a first longest match. For example, if the fields in a structure are:

```
variable string str1
constant byte bt1 = B
variable string str2
```

and the message received is:

```
aabbBddBd
```

HP DIS uses a first shortest match algorithm to parse this as:

```
str1 = aabb
bt1 = B
str2 = ddBd
```

vi uses a first longest algorithm. The vi command typed in as:

```
s/ \(.*\)B\(.*\)/str1=\1 str2=\2/
```

would result in str1 and str2 matches as:

```
str1=aabbBdd
str2 =d
```

Testing. The tests, test scripts, and results files can be generated automatically at compile time with a PSL compiler option. The tests are executed from a test script and the results appear in several data files:

- The action command file contains the test actions to be performed.
- The comparison results file contains a summary of the test paths.
- The trace data output file contains detailed test flows and variables.

The test generator walks the state table and generates the actions command file (Fig. 10). The test generator starts with the first state-event pair in the PSL program and generates commands to trigger the event. The test terminates at the state and event in the ECASE statement (last state, next state, event of last state). The data following the WURA (write to upper-level read area) statement is the equivalent of a message from the application. The data following the WLRA (write to lower-level read area) statement is the equivalent of a message from the device. A test case is generated for each subsequent state-event pair. The test cases (CASE 1; and CASE 2;) marked Good and commented out in Fig. 10 were already successfully executed. Test cases three and four were created by a second pass of the test generator based on the previous tests.

The test generator generates cases to trigger external events (messages from the application or device) by creating a message from the values involved. State-event pairs WAIT-ACK and WAIT-NAK (Fig. 9) were successfully generated because the test generator was able to use the structures ReplyAck and ReplyNak as the basis for triggering the events.

The test generator generates cases for internal events based on the associated values of the constants or variables involved. If the values will satisfy the event, the case is generated. If not, the case cannot be generated. Each case is rechecked on every pass to see if the variables involved have been changed in previous test runs. For more complete automatic test coverage, the PSL program variables can be set to values favorable for test case generation. In some cases, the contents of the messages in the actions command file must be altered to affect subsequent cases.

The test exerciser (Fig. 11) starts the interface under control of the run-time facility using the test configuration file (Fig. 12) and executes the test actions. At the conclusion of the test, the interface is terminated and the results are stored for examination.

Fig. 13 shows the comparison results file. The expected state-event pairs for the expected results and the actual results are always shown.

If the actual results differ from the expected results, the trace data output file (Fig. 14) can be examined to determine the cause. The trace data output file contains a detailed description of the data flow through the state table for each case executed by the test exerciser. It shows all incoming

```
Environment
  Runtime_name    =  Device_xx;
  device          =  Highway;
Constants
  Read                  = 1;
  Write                 = 2;
  Applic_read_Q         = 1;
  Applic_write_Q        = 2;
  Device_read_Q         = 3;
  Device_write_Q        = 4;
  Increment             = 1;
  Start_timer           = 1;
  Stop_timer            = 2;
  By_one                = 1;
  Calculate             = 1;
  Check                 = 2;
  DLE                   = 10h;
  STX                   = 2h;
  ETX                   = 3h;
  ACK                   = 6h;
  NAK                   = 15h;
  MaxRetry              = 5;              /* Max number of retries          */
  NoResponse            = 201;            /* Time-out return status         */
  HP_ID                 = 8;              /* Device identifer               */
  ComError              = 202;            /* Retry exceeded                 */
  StatusOK              = 0;              /* Message sent OK;               */
                                          /* return status                  */
  TimeOutVal            = 30000/*1000*/;  /* TO value = 1 s;                */
                                          /* test = 30 s                    */

Variables
  byte     RetryCount   = 0;              /* Retry counter                  */
  byte     bcc;                           /* Protocol block check character */
  byte     status       = 0;              /* Protocol status                */
  byte     dst          = 10;             /* Protocol destination device    */
  byte     src          = 0;              /* Protocol source device         */
  byte     cmd          = 0;              /* Protocol command               */
  byte     sts          = 0;              /* Protocol status                */
  integer  tns          = 1;              /* Protocol message number        */
  string   data         = '';             /* Data block                     */
  byte     Result;                        /* Dummy for DcIO                 */
  boolean  BccFlag      = TRUE;           /* Function for BCC check         */
  long     TimePeriod   = 0;              /* Timer value                    */
  string   Text         = '';             /* Bit bucket                     */
/* structures used to match messages */
  struct    ReplyAck   =  (DLE ACK);
  struct    ReplyNak   =  (DLE NAK);
  struct    DataPacket =  (DLE STX dst src cmd sts tns data DLE ETX bcc);
  struct    ReqPacket  =  (dst cmd data);
  struct    ReplyPacket =  (status data);
Events
/* Event: Event Type, Event definition        */
  send_message:  request,   ReqPacket;
  reply_message: response,  DataPacket;
  ACK:           response,  ReplyAck;
  NAK:           response,  ReplyNak;
  timeout:       internal,  TimePeriod >= TimeOutVal;
  retry_exceeded: internal, RetryCount >= MaxRetry;
  msg_ok:        internal,  BccFlag == TRUE;
  msg_nok:       internal,  BccFlag == FALSE;
States
  IDLE:          HOME;   /* Home state */
```

```
State_table

IDLE: send_message:
  DcIO(Read, Applic_read_Q, ReqPacket, , , Result)/
  /* START Build outgoing buffer */
  DcMove(ReqPacket.dst, DataPacket.dst)/
  DcMove(HP_id, DataPacket.src)/
  DcMove(ReqPacket.cmd, DataPacket.cmd)/
  DcMove(StatusOK, DataPacket.sts)/
  DcMove(tns, DataPacket.tns)/
  DcMove(ReqPacket.data, DataPacket.data)/
  DcCksum(Calculate, DataPacket.data, "BCC_AB", DataPacket.bcc)/
  /* END Build outgoing buffer */
  DcIO(Write, Device_Write_Q, DataPacket, , , Result)/
  DcMove(0, RetryCount)/
  DcCntr(Increment, tns, By_one)/
  DcClock(Start_timer, TimePeriod, TimeOutVal)
  :WAIT;
IDLE: reply_message:
  DcIO(Read, Device_read_Q, Text, , , Result)/
  DcIO(Write, Device_Write_Q, ReplyAck, , , Result)
  :IDLE;
WAIT: ACK:
  DcClock(Stop_timer, TimePeriod)/
  DcIO(Read, Device__read_Q, Text, , , Result)/
  DcClock(Start_timer, TimePeriod, TimeOutVal)
  :WAIT;
WAIT: NAK:
  DcClock(Stop_timer, TimePeriod)/
  DcIO(Read, Device_read_Q, Text, , , Result)/
  DcIO(Write, Device_Write_Q, DataPacket, , , Result)/
  DcCntr(Increment, RetryCount, By_one)/
  DcClock(Start_timer, TimePeriod, TimeOutVal)
  :WAIT;
WAIT: reply_message:
  DcClock(Stop_timer, TimePeriod)/
  DcIO(Read, Device_read_Q, DataPacket, , , Result)/
  DcCksum(Check, DataPacket.dst, "BCC_AB", DataPacket.bcc, BccFlag)
  :CHECK;
WAIT: timeout:
  DcClock(Stop_timer, TimePeriod)/
  DcMove(NoResponse, ReplyPacket.status)/
  DcIO(Write, Applic_write_Q, ReplyPacket, , , Result)
  :IDLE;
WAIT: retry_exceeded:
  DcClock(Stop_timer, TimePeriod)/
  DcMove(ComError, ReplyPacket.status)/
  DcIO(Write, Applic_write_Q, ReplyPacket, , , Result)
  :IDLE;
CHECK: msg_ok:
  DcIO(Write, Device_Write_Q, ReplyAck, , , Result)/
  DcMove(StatusOK, ReplyPacket.status)/
  DcMove(DataPacket.data, ReplyPacket.data)/
  DcIO(Write, Applic_write_Q, ReplyPacket, , , Result)
  :IDLE;
CHECK: msg_nok:
  DcIO(Write, Device_Write_Q, ReplyNak, , , Result)/
  DcCntr(Increment, RetryCount, By_one)/
  DcClock(Start_timer, TimePeriod, TimeOutVal)
  :WAIT;
```

Fig. 9. *PSL (Protocol Specification Language) protocol program.*

Action Routines

HP DIS is shipped with a wide variety of routines to ease the creation of protocol interfaces. If a required action routine cannot be found in the HP DIS action routine library, the user can write a user action routine.

A protocol interface consists of two components: a finite state machine and its corresponding internal tables. The finite state machine is customized for the HP DIS and user action routines. The internal tables are: 1) an identifier table consisting of constants and variables, 2) an event table consisting of event IDs and event expressions, and 3) a state table consisting of current state ID, event ID, action list, and next state ID tuples.

In the state table, the action list specifies HP DIS action routines or user action routines. Action routines operate on the variables in the identifier table. HP DIS provides a header file, DcTypes.h, which can be used by user action routines written in the C programming language to simplify parameter passing.

The HP DIS-supplied action routines are listed below.

DcBufMod	Buffer modification
DcCksum	Checksumming
DcClock	Timer
DcCntr	Counter
DcConvert	Data conversion
DcDelay	Delay
DcEncode	Data encoding
DcExit	Terminating the protocol interface
DcFlag	Flag setting
DcIO	Input/output
DcLogAd_AB	Address builder
DcMove	Move
DcScan	Data scanning
DcTabInit	Table initialization
DcTabScan	Table scanning
DcBufMod	Buffer modification

An Example

The HP DIS action routine DcClock activates or deactivates a time counting facility. Timer counters are caller-supplied HP DIS variables. The HP-UX system interval timer ITIMER_REAL is used to update the time counters in real time. A SIGALRM signal is delivered when the system interval timer ITIMER_REAL expires, and all active timer counters are updated. Updating a time counter can trigger an event if the timer counter exceeds a specified time-out value. In the following example the event TimeOut is triggered when time_counter is greater than 60000 (60 seconds).

```
Variables
  long time_counter;
Events
  TimeOut : internal, time_counter > 60000;
State_Table
  ...
  ...
  DcClock(1, time_counter, 1000)          /* Start time counting */
  ...
  ...
  Idle : TimeOut :                        /* Time-out detected */
  DcClock(2, time_counter)                /* Stop time counting */
  : Idle;

  ...
  ...
```

messages, state-event pairs, and values of all variables after every action associated with each state-event pair. The variable values are useful for checking the results of actions even when the correct path is executed.

This example has shown that by using tools and a subsystem approach, a factory-floor device protocol can be modeled and produced.

Configurations

Fig. 15 shows various configurations for HP DIS-built interfaces. Interface schemes can use a single protocol interface or multiple protocol interfaces. These protocol interfaces can be stacked in series or configured in parallel. When multiple devices are serviced, even more choices can be made: each device can be serviced by its own dedicated protocol interface, or multiple devices can be serviced by a generalized protocol interface.

Fig. 15a shows the simplest configuration. Here, one protocol interface handles one port and one device.

Fig. 15b shows three protocol interfaces that work together. Message processing that is common to all ports is done in the lower-level PI1. The message is passed to the upper-level PI2 and PI3 for device-specific processing. For example, PI1 can collect all messages from multiple de-

```
/*  Time_Stamp:   608506312  */
/*                Run-Time Name                State Table File Name  */
Runtime_Name    Device_xx                      /users/test/Device_xx.st;

/* CASE 1; */
/*    Good */
/*    State              Command */
/* IDLE                  WURA '\012\000'; */
/*    End of case */
/* ECASE IDLE WAIT send_message; */

/* CASE 2; */
/*    Good */
/*    State              Command */
/* IDLE                  WLRA    '\020\002\012\000\000\000\000\000  */
/*                               \001\020\003\000'; */
/*    End of case */
/* ECASE IDLE IDLE reply_message; */

CASE 3;
/* State                Command */
IDLE                    WURA    '\012\000';
WAIT                    WLRA    '\020\006';
/* End of case */
ECASE WAIT WAIT ACK;

CASE 4;
/* State                Command */
IDLE                    WURA    '\012\000';
WAIT                    WLRA    '\020\025';
/* End of case */
ECASE WAIT WAIT NAK;
```

Fig. 10. *Action command file.*

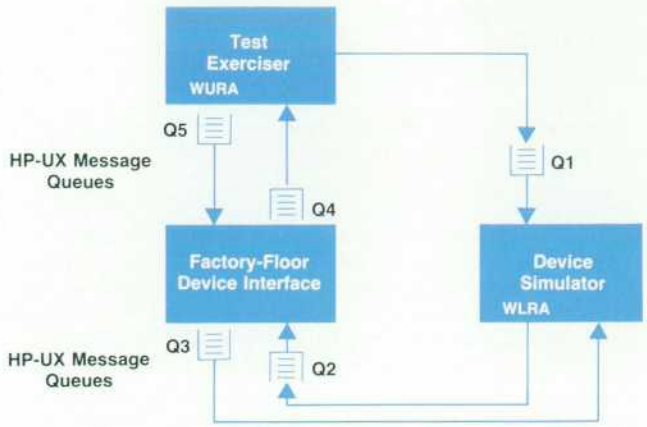

Fig. 11. *Testing interfaces.*

vices, perform checksums, and pass them to the next level. This ensures that all messages are acknowledged promptly by a dedicated protocol interface, while less time-critical functions are handled by separate protocol interfaces.

Fig. 15c shows three protocol interfaces, each dedicated to a port. Device-specific message processing is done for each port. The upper-level PI4 directs and organizes messages before passing them up to the application.

A developer can choose where to put common functions. The performance will be slightly better when the number of protocol interfaces in serial is smaller, since fewer messages are passed between processes. On the other hand, a centralized function may be desirable because it simplifies the system design.

Performance

An HP DIS system is easier to construct than a similar application in C code, but this is achieved with some loss of performance compared to C code. In an HP DIS system, functionality is split across five (or more) separate HP-UX processes. In C code, all the functionality could reside in a single process. For example, HP DIS port management is handled by separate read and write port processes with

```
PI_DEFINITIONS

  Runtime_Name = Device_xx;
  Runtime_Type = T;

  Runtime_Name = PMDPSS;
  Runtime_File_Name = /usr/bin/PMDPSS; /* Device Simulator   */
  Runtime_Type = T;

QUEUE_DEFINITIONS
  Queue_Name = Q1,Q2,Q3,Q4,Q5;
  Queue_Link
  Q5 > Device_xx;
  Device_xx > Q3;
  Q4 < Device_xx;
  Device_xx < Q2;
  PMDPSS < Q3;
  PMDPSS > Q2;
  Q1 > PMDPSS;
```

Fig. 12. *Test configuration file.*

```
Runtime_Name: Device_xx

Execution_Number: 1 Case_Number: 1

  Status: Cases identical in file Device_xx.tr and file
          Device_xx.da

  Event Path taken and Case Status in file Device_xx.tr:
  [IDLE:send_message,DCIO;DCMOVE;DCMOVE;DCMOVE;DCMOVE;DCMOVE;
  DCMOVE;DCCKSUM;DCIO;DCMOVE;DCCNTR;DCCLOCK;WAIT]
  Case_Status: 0

  Event Path taken and Case Status in file Device_xx.da:
  [IDLE:send_message,DCIO;DCMOVE;DCMOVE;DCMOVE;DCMOVE;DCMOVE;
  DCMOVE;DCCKSUM;DCIO;DCMOVE;DCCNTR;DCCLOCK;WAIT]
  Case_Status: 0

Execution_Number: 1 Case_Number: 2

  Status: Cases identical in file Device_xx.tr and file
          Device_xx.da

  Event Path taken and Case Status in file Device_xx.tr:
  [IDLE:reply_message,DCIO;DCIO;IDLE]
  Case_Status: 0

  Event Path taken and Case Status in file Device_xx.da:
  [IDLE:reply_message,DCIO;DCIO;IDLE]
  Case_Status: 0
```

Fig. 13. *Comparison results file.*

```
Execution_Number: 1
Case_Number: 1
Runtime_Name: Device_xx
Trace_Data_Available
Action_Command: WURA
Protocol_Message_Transmission_Elapsed_Time: Thu Apr 13 14:33:30 1989
Protocol_Message_Data_Packet: '\000\ 012\000 '
Status: Triggered
State: IDLE
Event: send_message
Variable_Retrieval_Elapsed_Time: Thu Apr 13 14:33:30 1989
State_Table_Variables:
ReplyPacket.data = ' '
ReplyPacket.status = 0
ReqPacket.data = ' '
ReqPacket.cmd = 0
ReqPacket.dst = 10
DataPacket.bcc = 0
DataPacket.data = ' '
DataPacket.tns = 1
DataPacket.sts = 0
DataPacket.cmd = 0
DataPacket.src = 0
DataPacket.dst = 10
Text = ' '
TimePeriod = 0
BccFlag = True
Result = 0
data = ' '
tns = 1
sts = 0
cmd = 0
src = 0
dst = 10
status = 0
bcc = 0
SYS_ERR = 0
Status: Triggered
State: IDLE
Event: send_message
Action: DCIO
Variable_Retrieval_Elapsed_Time: Thu Apr 13 14:33:30 1989
State_Table_Variables:
ReplyPacket.data = ' '
ReplyPacket.status = 0
```

Fig. 14. *Trace data output file.*

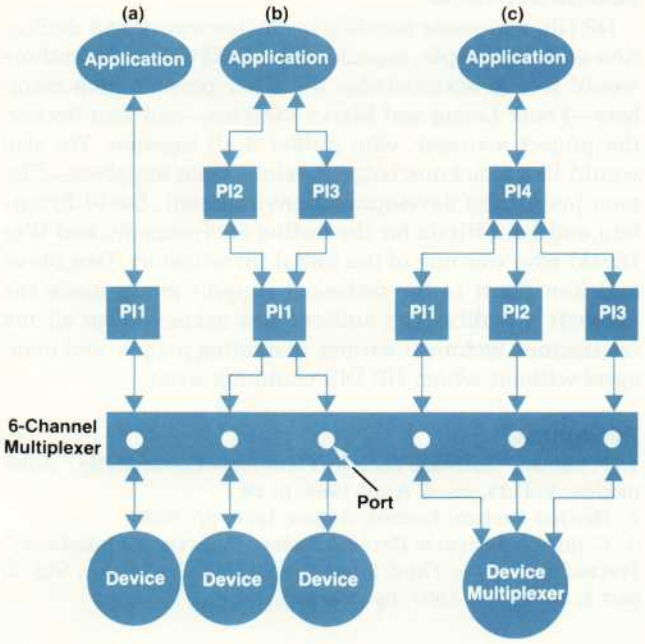

Fig. 15. *Configurations for HP DIS-built interfaces. (a) One protocol interface handles one port and one device. (b) Three protocol interfaces work together. (c) Three protocol interfaces, each dedicated to a port, with an upper-level interface (PI4) directing and organizing messages.*

connected HP-UX message queues. HP DIS handles the message buffering. This decreases development time since port configuration and buffer management code does not have to be written. However, the performance of this port interface will fall short of a similar interface with integrated port management functions.

It is also relevant that HP DIS is an HP-UX application. An HP-UX cell controller, whether written in HP DIS or in C, is subject to normal HP-UX timesharing policies, and will have nondeterministic response times. With HP-UX on HP 9000 Series 800 computers, processes can be run under a real-time priority to decrease the chance that a process will be preempted. HP DIS uses this HP-UX extension. With real-time HP DIS processes, response time variability can be decreased.

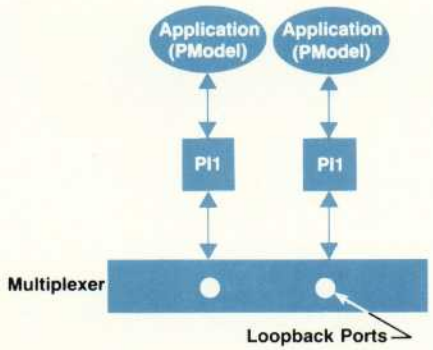

Fig. 16. *HP DIS performance test model for multiple ports. PModel is a simulated HP DIS application.*

Performance Test Results

HP DIS performance studies were conducted to answer these questions:

- What is the performance on HP 9000 Series 300 and Series 800 computers?
- What is the throughput of an HP DIS interface?

The flexibility of HP DIS allows device interface modules to be configured and combined in an infinite number of ways. A simple model was chosen that gives representative data involving the major items contributing to performance. Fig. 16 depicts a typical configuration. An application (PModel) is connected to a device interface module (PI1), which is connected to an HP-UX RS-232 multiplexer port. The port has a physical loopback connection and all data written to the port is immediately read back from the port. Each port has one PModel. A fixed-length message is sent to the port by a PModel and returned unchanged. Because the application program waits for each message to return before sending another, only one message is in the loop at a time per PModel. Throughput data is averaged over 20 transmissions for various message lengths using one, then

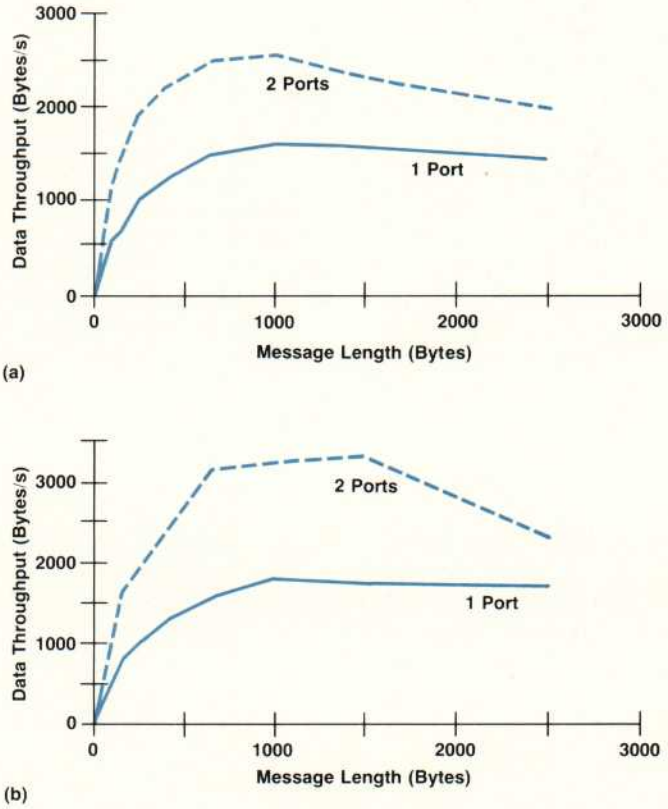

Fig. 17. *Loopback response time for performance tests using the HP DIS application PModel on (a) HP 9000 Model 375 and (b) HP 9000 Model 832 computers (HP DIS 2.2 on HP-UX 7.0).*

two PModels.

Fig. 17 shows the data throughput of an HP 9000 Model 375 and an HP 9000 Model 832, both with 16M bytes of memory, under the HP-UX 7.0 operating system. The throughput in Fig. 17 reflects the transfer of data one-way. The curves show the data throughput for one PModel and the sum of the data throughputs for two PModels.

The throughput decreases with message sizes above 1000 to 1500 bytes because HP DIS is performing message matching (see "Matching Messages," page 67). HP DIS matches raw byte streams to the user's definition of the message.

Summary

The Hewlett-Packard Device Interface System, HP DIS, is a tool that eases the development of communication links between computers and factory-floor devices. Interfaces can be developed more quickly than with conventional code. Devices can be simulated, and testing is mostly automated. Communication links can be scaled, using only the routines needed for the application at hand. Through the use of this tool, factory-floor devices from many vendors can be mixed and matched.

HP DIS can improve productivity, reliability, development costs, and market response and reduce support costs for device interfaces.

Acknowledgments

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Measurement of R, L, and C Parameters in VLSI Packages

Developed to verify the electrical models of a 408-lead multilayer ceramic package, this measurement technique can measure the very small inductances, capacitances, and resistances that are typical of high-performance packages. It does not require extraction of RLC parameters from time-domain reflectometer measurements.

by David W. Quint, Asad Aziz, Ravi Kaw, and Frank J. Perezalonso

THE NEED FOR HIGH-PERFORMANCE, high-pin-count IC packaging with a large number of I/O connections has brought about a project to design and characterize a multilayer ceramic PGA (pin-grid array) capable of providing up to 320 I/O lines at an operational frequency in excess of 60 MHz. Our challenge is to produce a package that brings the performance advantages of multilayer cofired ceramic technology to high-lead-count, high-power VLSI circuits. The package currently in development will mount a 14-mm-square CMOS chip.

Fig. 1 is a cross-sectional drawing of the package. The package contains 12 metallization layers, which are used for signal, power, and ground routing, and uses three-tier bonding from the chip to the bonding pads on the package. The top two bonding tiers on the package are exclusively for signal or I/O connections. The bottom bonding tier is reserved for power supply and ground connections. The signal routing layers provide a stripline environment and there is a ground plane adjacent to each of the power supply planes.

The pads on the chip are spaced at an effective pitch of approximately 110 micrometers (0.00433 inch). We have been able to match this pitch on the package by using two signal bonding tiers. Power supply connections are divided into eight groups for flexibility and noise isolation. The chip mounts directly on a copper-tungsten heat spreader that is used for heat dissipation. The heat spreader is also connected to ground.

Electrical Modeling

The designers of system processing units put considerable effort into system simulations. One of their main concerns is the amount of noise induced on logic V_{DD} (logic V_{DD} powers the internal circuitry of the IC) and logic GND (ground). Another concern is noise on signal lines. Noise is caused by power and ground bounce* and by coupling of signals from one line to another. The main source of this noise is the familiar Ldi/dt term, which arises from logic and I/O driver currents flowing in the inductance of the package and circuit board conductors. To produce meaningful simulations, it is necessary to include models of all these components in the circuits. The simulations are particularly sensitive to the IC package model, since the package lead inductance accounts for most of the inductance L in the Ldi/dt term for computing power supply bounce. The values of the power supply inductances that need to be added in the simulations range from about 70 picohenries to about 0.5 nanohenry. In addition, ground models

*"Bounce" in ground and power supplies refers to a temporary droop or rise in the supply voltage caused by large currents drawn by devices using the supplies.

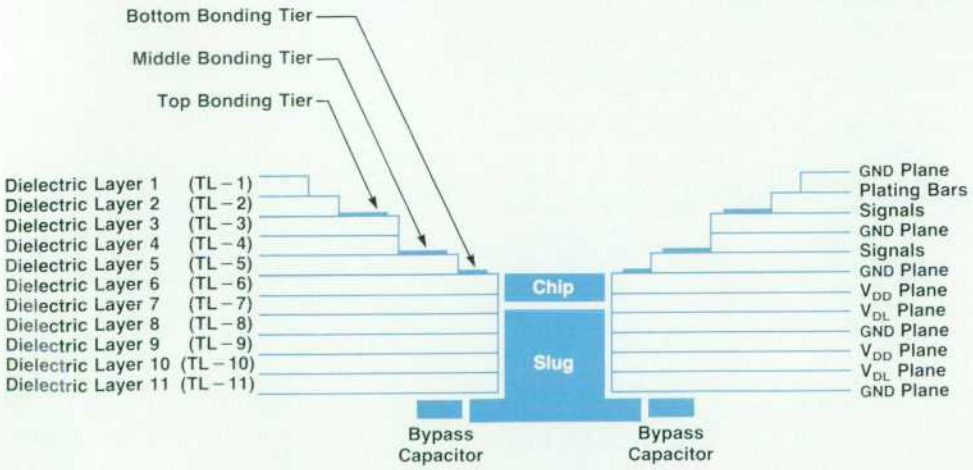

Fig. 1. *PGA (pin-grid array) construction detail (not to scale). All dielectric layers are 0.008 inch thick.*

and signal trace models including cross coupling need to be included in the system simulations.

Model Verification

Creation of electrical models for the PGA was facilitated by various software tools and by leveraging previous work done on the subject. Verifying that these models were correct was much more challenging and is the main topic of this paper. Models were verified by comparing package parameters calculated from the models with measurements on an actual PGA package.

Most high-frequency measurements are done using a network analyzer or a time-domain reflectometer (TDR). Both instruments measure reflections from discontinuities. The problem with using a TDR lies in the interpretation of the results when the time delay through a discontinuity is short compared with the rise time of the propagating pulse. The PGA package signal leads consist of stripline transmission lines with a signal propagation time between 100 and 200 picoseconds and a characteristic impedance of approximately 37 ohms. Considering the time delay through the package, a TDR pulse with a rise time of about 20 picoseconds is necessary to give good resolution. Using such a fast rise time, skin effect, dielectric losses, and reflections from the test fixture and interconnections distort the reflection test signals to such a degree that it is virtually impossible to extract an RLC circuit for the package itself. A TDR measurement also does not give numbers for first-order and second-order mutual inductances and capacitances between signal lines. TDRs are especially unsuitable for the power supply planes because of the extremely low characteristic impedances of these planes (5Ω or less). A TDR does not have the ability to drive such a low-impedance load.

Since simulations are done with the HP Spice software package using models made up of discrete R, L, and C elements, these are the parameters that need to be verified. Because TDR or direct measurements with an impedance analyzer cannot give this kind of detail, it was deemed necessary to develop another measurement technique, which is described in the following sections.

Capacitance Measurement

A typical PGA signal trace structure, including the signal wirebond and the PGA pin, is modeled in the passive circuit of Fig. 2. This is a useful model for HP Spice simulations. It can also be approximated in the form of transmission lines with $Z_o = \sqrt{L_1/C_1}$ and propagation time $t = \sqrt{L_1C_1}$. The transmission line approach is more difficult to apply when the mutual coupling and resistive losses are important. This is the case in any IC package where a number of I/O lines and internal circuits are switching simultaneously. The RLC equivalent is applicable to any circuit where the time delay of the element is less than about half the shortest rise time of the propagating signal. In the case of pin-grid array packages, the odd geometry gives the device non-TEM properties; for example, the capacitive and inductive coupling coefficients are not equal.

To overcome the shortcomings of traditional measurement techniques, the following method is used. The R, L, and C values in Fig. 2 are measured using slightly different electrical circuits. The only source used is a ramp generator and the only detector used is an oscilloscope with a matched 50Ω input impedance. Fig. 3 illustrates the measurement of a capacitance such as the coupling capacitance between the two traces. The use of a ramped input signal cancels effects of circuit elements that are not under test and aids in the interpretation of results. The charging current i(t) defines the voltage across the oscilloscope's channel 2 inputs and the unknown capacitance C_x can be calculated from

$$C_x = V_{max}/(R_{scope2}dV_{in}/dt) \quad (1)$$

where voltage is measured at the center time of the V_{gen} ramp.

The voltage V_{out} is small, but its accurate measurement is important to the determination of the parameter values. The measurements that must be taken on the oscilloscope screen are the slope of the V_{in} ramp (dV_{in}/dt) and V_{max}, the plateau voltage on V_{out}. Matched coaxial cables between the instruments and the device under test introduce time delays, but do not introduce any additional factors in the equation for C_x above. For example, losses in the coaxial cables from the sample to the oscilloscope will introduce no error if they are the same length for both channels, since the measurement depends on the quotient of the measured voltages. The voltage drops across the series resistance and inductance in the trace are small, since they are in series with the capacitive impedance. The capacitive impedance dominates the current, so the resistive and inductive volt-

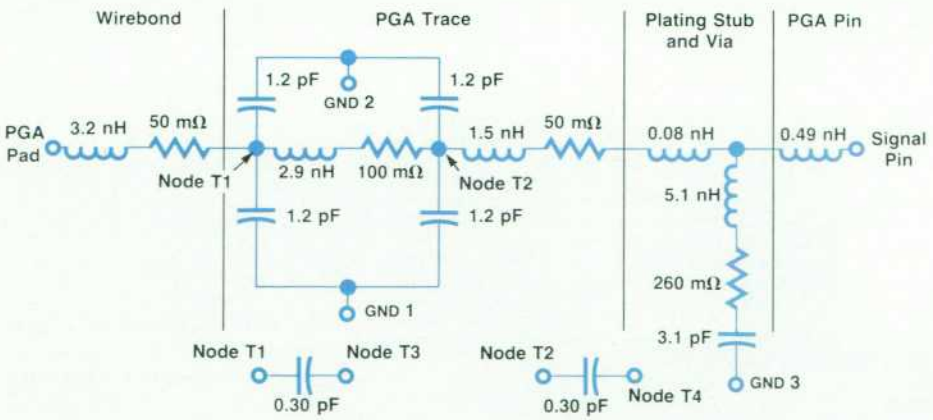

Fig. 2. *Passive circuit model of a typical PGA signal trace structure, showing typical trace parameters. Nodes T3 and T4 are corresponding nodes on the adjacent signal trace for capacitive coupling. Inductive coupling is not included in this model.*

ages can be ignored. In addition, the capacitive loading on the V_{out} side is of little consequence, because the voltage being measured (the plateau top) is essentially constant. The capacitance on the V_{out} side will drop out of the measurement equation if the time constant $C_{out}R_{scope2}$ is much less than the test pulse rise time.

C_x can be measured quite easily at several pulse rise times, and the calculated values of C_x can be compared for the different measurements. The longest pulses will give smaller plateau voltages, increasing the importance of the signal-to-noise ratio of the equipment, while the shorter pulses will cause the measurement to depart from its true value in a systematic way as the parasitics in the test jig become more dominant. In the PGA and other common packages, there is usually a wide range of pulse rise times that give the same answer for the value of the tested element.

In this and all the other test situations, the test jig parameters must be measured without the package and subtracted from the values obtained with the package in place. The design of the test jig is important and must include matched-impedance lines with connections as close as possible to the PGA to minimize the parasitics of the test jig. Good ground integrity is important, since large parasitics can be introduced quite easily. Poor connections are easily found using the real-time display of the oscilloscope. Movement of a poor connection will produce corresponding wiggling of the oscilloscope trace and a poor connection can usually be located quickly and corrected. Once the test jig and cabling are connected properly, movement of the cables should produce no noticeable movement of the oscilloscope traces. This troubleshooting ability is another benefit of this technique.

Inductance Measurement

Inductances are measured by applying ramped currents instead of ramped voltages to the traces under test. This is arranged by shorting the wirebonds of the PGA traces to the PGA ground circuit. This circuit is shown in Fig. 4.

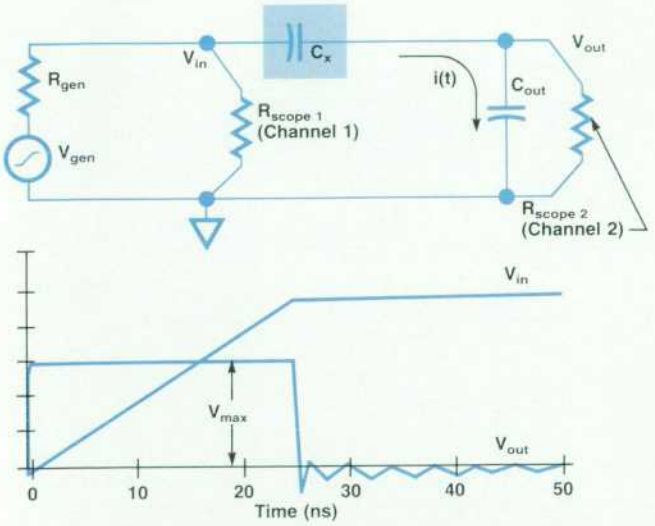

Fig. 3. *Capacitance measurement circuit and voltage waveforms.*

The input impedance of the signal trace, represented by L_x in series with R_x, is low compared with the effective source impedance of the generator and the oscilloscope in parallel ($R_{gen}\|R_{scope}$), so the input current is determined solely by the test equipment connected to the circuit. Thus, current $I(t) = V_{gen}(t)/R_{gen}$, since the package under test is virtually a short circuit. Virtually all of the current from the ramp generator flows through the package trace, so the voltage V_{out} is determined solely by the trace inductance and resistance. Again, if the rise time of V_{gen} is much greater than the time constant of the generator and package inductance, the voltage across the package quickly becomes $V_{out} = L_x dI/dt + R_x I$. The output pulse consists of the sum of two components: (1) a flat-topped pulse like the one in the capacitance measurement, and (2) a ramp proportional to the input current. If we separate the two voltages in Fig. 4, call the inductive voltage V_{lx}, represented by the plateau voltage, and call the resistive voltage V_{rx}, the final voltages after the ramp can be found from:

$$L_x = V_{lx}R_{gen}/(dV_{gen}/dt) \quad (2)$$

$$R_x = V_{rx}R_{gen}/V_{genmax}, \quad (3)$$

where dV_{gen}/dt is the slope of the ramp voltage and V_{genmax} is the final voltage of the V_{gen} step (see Fig. 4).

The bounce caused by the partial inductance of the PGA ground net can be canceled by driving a third (uncoupled) signal trace, grounded to the shield at the inner lead bond, with a negative-going ramp of the same magnitude. The third lead must be uncoupled so that mutual inductance does not contribute unwanted voltages to the measurement.

Test Fixture and Parasitics

For each of the parameters that we measured (inductance, capacitance, mutual inductance, and mutual capacitance) we had to build a different set of probes. The parasitics of

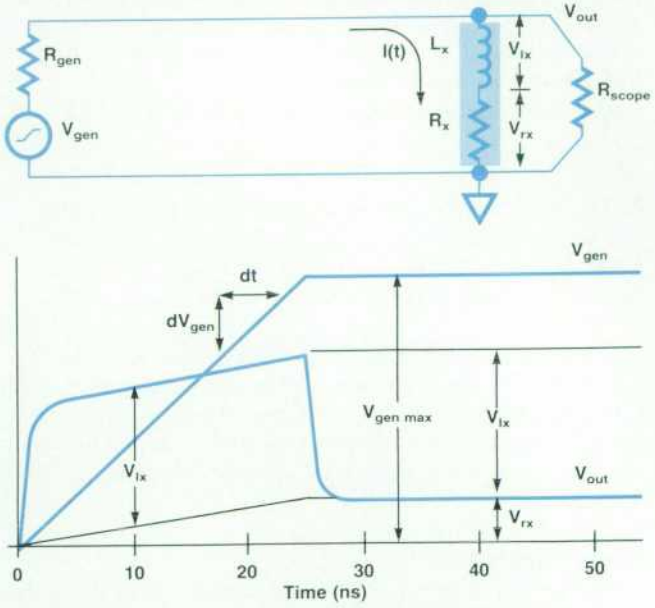

Fig. 4. *Inductance measurement circuit and voltage waveforms.*

these probes were zeroed out before and after each measurement to make sure that the characteristics of the probes did not change during the measurements. This was especially important in the case of the power supply inductance measurements because the characteristics of the probes were comparable in magnitude to those of the package.

Signal Models

Signal trace models were calculated using Stripcal[1] to calculate the lumped elements in the trace model between the PGA bond pad and the base of the pin. Ind3[2] was used to calculate the inductances (both self and mutual) for the wirebonds. The measurements were done on a 408-pin PGA that had a test chip mounted and bonded in it. For the inductance measurements, all the wirebonds were shorted together on the chip. For the capacitance measurements, all the signal wirebonds were isolated.

Resistance measurements are not discussed in detail because they are straightforward and because the measured values of the tungsten metallization sheet resistance were between 5 and 7 milliohms/square, well below the maximum specification of 13 milliohms/square. In addition, the resistance of the ground and power supply routing was less than 5 milliohms, which was not considered significant.

The inductance measurement results were as follows:

Parameter	Measured	Calculated	Difference
Self L (upper tier)	15.1 nH	15.2 nH	1%
Self L (middle tier)	14.9 nH	14.6 nH	2%
Mutual L (middle tier)	3.64 nH	3.21 nH	12%
Mutual L (upper tier)	4.7 nH	4.5 nH	4%
WB coupling (1st order)	2.0 nH	2.1 nH	5%
WB coupling (2nd order)	1.4 nH	1.5 nH	7%

Note: WB = wirebond.

The sources of error for the signal inductance parameters are: (1) the routing on the chip, (2) variations in the length and the shape of the wirebonds and traces, and (3) imperfections in the ground planes.

The capacitance measurement results were as follows:

Parameter	Measured	Calculated	Difference
Self C (upper tier)	10.1 pF	9.5 pF	6%
Self C (middle tier)	6.5 pF	6.3 pF	3%
Mutual C (upper tier)	0.7 pF	0.5 pF	29%
Mutual C (middle tier)	0.6 pF	0.5 pF	17%

The sources of error in the signal capacitance measurements are: (1) the capacitance of the pin braze pads, and (2) the capacitance of the vias and the associated cover dots. The capacitance between the wirebonds and between the pins was found to be less than 0.1 pF and has been ignored.

Power Supply Models

The measurements were done in the same way as for the signal traces. The results were as follows:

Parameter	Measured	Calculated	Difference
Self L of V_{DD}	97 pH	79 pH	19%
Self L of V_{DL} (group 1)	0.88 nH	0.77 nH	14%
Self L of V_{DL} (group 2)	1.18 nH	1.06 nH	11%
Self C of V_{DD}	4.96 nF	4.92 nF	1%
Self C of V_{DL} (group 1)	0.66 nF	0.62 nF	6%
Self C of V_{DL} (group 2)	0.5 nF	0.47 nF	6%

Note: V_{DD} is the logic power supply voltage and V_{DL} is the I/O driver supply voltage.

V_{DD} Measurement Errors

In the V_{DD} inductance measurements, the topology forced us to put all eight ground wirebonds on the same side of the V_{DD} wirebonds instead of four on each side as the chips are actually bonded. Moving all the ground wirebonds to one side of the V_{DD} wirebonds may increase the inductance of the wirebonds by up to 50%. This effect accounts for most of the difference between the calculated and measured values of the V_{DD} inductance. Fig. 5 compares the measurement bonding pattern and the pattern the package was designed to use in actual operation. Another source of error is the shape (loop height, length, etc.) of the wirebonds. The wirebond shape may be turn out to be different from the one that was analyzed.

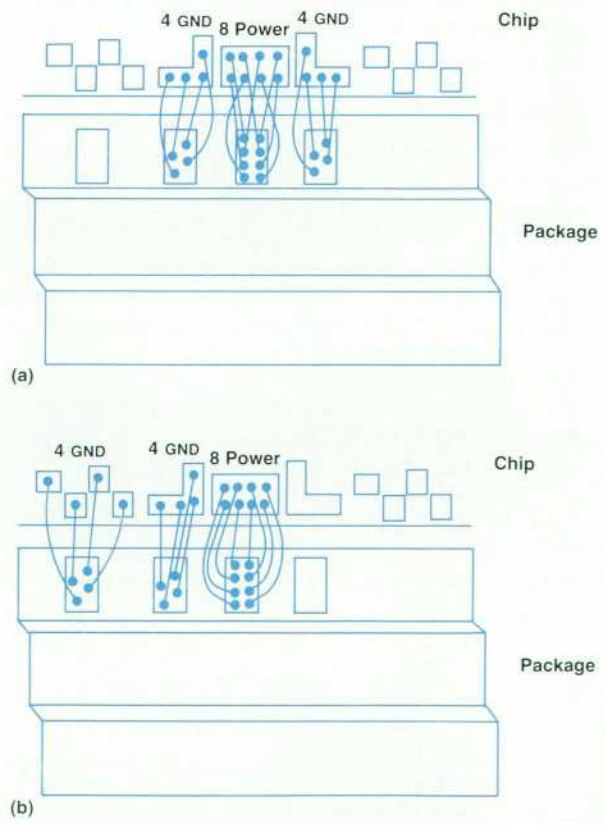

Fig. 5. *To measure V_{DD} inductance, it was necessary to put all eight* GND *wirebonds on the same side of the V_{DD} wirebonds, as shown in (b). In actual service, the wirebond pattern is as shown in (a). This accounts for most of the difference between the measured and calculated values.*

V_{DL} Measurement Errors

The wirebonding pattern may vary in the V_{DL} bonds. In the calculations for the V_{DL} inductance, we also did not take into account the inductance of the epoxy routing on the chip.

The power trace capacitance measurements were done without the bypass capacitors because the 0.1-μF nominal value of the bypass capacitor is very large compared to the capacitance parameter that we were trying to measure. A very high degree of correlation was obtained between measurements and calculations.

Conclusions

It is important to be able to verify electrical models of packages used in high-performance systems. Time-domain reflectometry cannot give the kind of detail needed for model verification, and it is very difficult to derive an RLC circuit from the results.

The measurement technique described in this paper[3] overcomes the problems associated with TDR measurements. Inductance is measured while capacitance is shorted out, and capacitance is measured on open-circuit traces so inductive effects are negligible. Slow rise times of input voltage pulses make it possible to avoid transmission line effects. A feature of this method is that the measurements can be made with readily available digital oscilloscopes and pulse generators.

Good correlation between the calculated and measured results for the PGA package was obtained. This measurement technique has also been used to measure parameters of TAB (tape automated bonding) packages, printed circuit PGAs, and printed circuit board connectors with good results, and could also be useful in other electrical model verification experiments.

Acknowledgments

We would like to thank Ken Lee and Ralph Liu, who assisted with this effort and provided invaluable ideas and advice. We would also like to thank Bob Crawford and Ron Bernard for designing the probes and writing the software for the measurements, and Pauline Prather for her support and expertise in bonding and assembling the test devices. Colorado IC Division assembly, particularly Dave Gilzean, helped wholeheartedly to make this effort possible.

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Statistical Circuit Simulation of a Wideband Amplifier: A Case Study in Design for Manufacturability

Statistical variations of integrated circuit parameters are often correlated, not independent. Examples are side-by-side resistor values and matched transistor gains. Accounting for these correlations using principal component analysis can make statistical simulation an accurate predictor of manufacturing data.

by Chee K. Chow

IN INTEGRATED CIRCUIT DESIGN, there is a need for statistical circuit simulation that can accurately project circuit performance distributions in manufacturing. There are two reasons for this need. First, being able to project the performance distributions precisely in the design phase enhances the chance of a first-pass success. Thus, the cycle time from the design phase to manufacturing release can be significantly reduced. Second, simulation can serve as a diagnostic tool to identify hidden process problems. For example, large discrepancies between the simulated and manufactured distributions frequently indicate process anomalies not previously discovered.

A simple approach to statistical circuit simulation is to perform a large number of Monte Carlo simulations.[1] The inputs to these simulations are computer-generated random circuit parameters based on the means and standard deviations of the circuit elements extracted from the manufacturing data. A significant drawback of this approach is that it does not account for the highly correlated nature of the device parameters within an integrated circuit die and also among dice. Consequently, it rarely gives accurate predictions.

In integrated circuits, device parameter variations are separable into two types. Variations across many dice, wafers, or fabrication lots are random in nature, while those within a die are highly correlated. Examples of the latter type are the side-by-side layouts of resistors and matched transistor pairs. At present, commercially available circuit simulators do not address these intercorrelations, so they do not provide the information needed.

This article describes a circuit simulator study that accounts for both the intradie device correlations and the lot-to-lot random variations. The technique used is based on principal component analysis, a branch of multivariate statistics. Examples are presented showing the application of this technique to a custom wideband bipolar amplifier IC used in the HP 54503A digitizing oscilloscope. The technique was used to set an accurate specification early in the design stage and to identify a process problem affecting the circuit performance.

Principal Component Analysis

Consider an integrated circuit having n parameters such as resistor values and transistor gains. These parameters vary statistically from lot to lot, from wafer to wafer, and from die to die because of the time and spatial variations of the fabrication process. The manufacturing distributions for this IC can be simulated if an ensemble of n-variable vectors can be generated having the same statistical variation as the circuit parameters. The accuracy of these simulations depends to a large extent on how accurately the intercorrelations of the n variables are accounted for.

The n-variable vectors can be generated by multivariate statistical techniques,[2,3] starting from the correlation matrix of the n variables. Multivariate statistics analyzes the structure of complex statistical variables to identify latent factors (factor analysis) or the principal components (principal component analysis). A comprehensive treatment of this subject can be found in the literature.[2,3] Multivariate statistics has been used extensively by behavioral scientists to analyze latent factors responsible for certain behavior traits. Its applications to manufacturing problems, based on our literature survey, have been very limited.[4,5,6,7]

One method of solving for the ensemble of n-variable vectors is based on principal component analysis techniques. Briefly, principal component analysis describes the variances of the n random variables in terms of a set of mutually orthogonal or statistically independent (uncorrelated) variables known as principal components. Each principal component accounts for a portion of the total variance larger than the succeeding components. Statistical ensembles of the n variables can be readily generated from random numbers after the transformation to the principal components because of the statistical independence of the principal components.

The ensemble of n-variable vectors is generated in a closed-form solution starting from the n-variable correlation matrix **R**, provided that the eigenvalues of **R** are all positive and the variables are normally distributed. For a set of n circuit variables, $y_1, y_2, \ldots, y_n$ having a correlation matrix **R**, it can be shown that the ith statistical variable

y_i is given by the expression:[2,3]

$$y_i = \left(\sum_j \lambda_j^{1/2} \gamma_{ij} x_j\right) \sigma_i + \mu_i \qquad (1)$$

where $x_1, x_2, \ldots, x_n$ are normally and independently distributed random variables (the principal components). The values for the x_i in equation 1 are chosen randomly and independently. This is possible because the x_i are statistically independent.

The λ_i in equation 1 are the eigenvalues of **R**. The μ_i and σ_i are the mean and standard deviation of the ith variable. γ_{ij} is the jth component of the ith eigenvector of **R**. The statistical measures for these variables are obtained from volume manufacturing data.

Circuit Simulation Algorithm

A circuit simulator[6] was written in C and HP-UX scripts. It runs on an HP 9000 Series 370 workstation. The algorithm of this program is shown in Fig. 1. It consists of three modules:

- A statistical analysis package performs all the computations according to equation 1.
- A parser retrieves these correlated vectors and generates the HP Spice text files.
- HP Spice performs the simulations.

The user is required to input three pieces of information: (1) the HP Spice text file, (2) the correlation matrix of the circuit variables, and (3) the means and standard deviations of the circuit variables. Data for (2) and (3) has been compiled from volume production measurements for many HP fabrication processes.

The confidence limits of the simulated distributions vary as the square root of the number of simulations.[1] Based on numerous case studies, about 100 simulations are adequate to project a 95% confidence limit, even for a fairly complex system. Although these Monte Carlo simulations are computationally intensive, with the emergence of widely available high-performance workstation-class computers, they can be routinely performed. A typical 200-sample simulation takes 149 seconds on an HP 9000 Model 370 workstation.

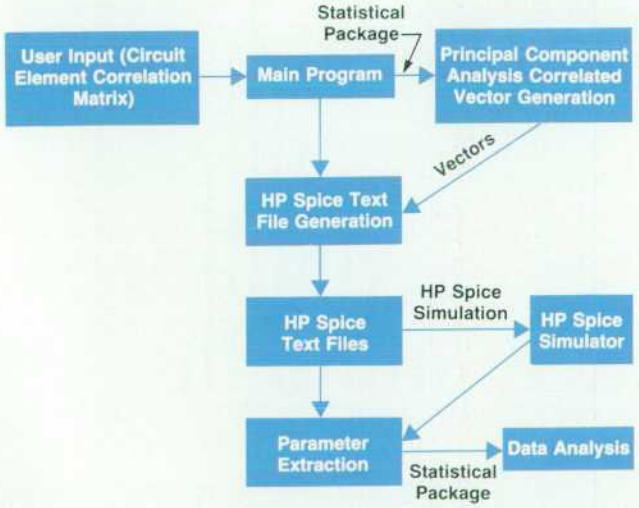

Fig. 1. *Statistical circuit simulation algorithm.*

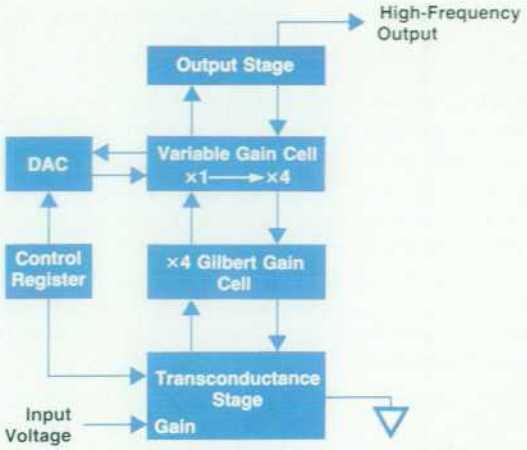

Fig. 2. *Simulation was used to set the minimum gain specification for this programmable gain circuit portion of an integrated amplifier IC.*

Case Study

The merits of this statistical circuit simulator are illustrated by two applications during the manufacturing release of a custom high-speed integrated circuit.

The circuit is an integrated amplifier fabricated using the HP5 process, a 5-GHz f_T oxide isolation process. The IC is used in the HP 54503A low-cost, high-performance digitizing oscilloscope. This custom IC is the heart of an amplifier/attenuator assembly that accurately reproduces signals from dc to 500 MHz and from 40 mV to 40V with ac or dc coupling and a constant output dynamic range of 500 mV. The IC consists of nine functional blocks. On-chip

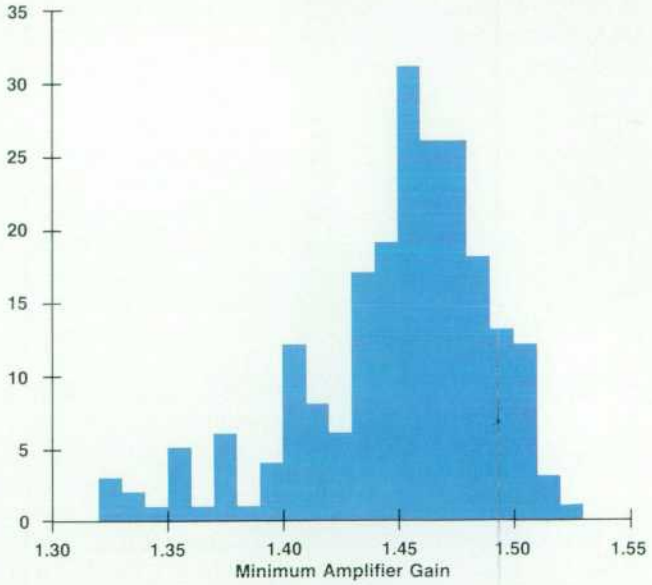

Fig. 3. *The distribution of the minimum gain from 220 correlated simulations has a mean of 1.44 and a standard deviation of 0.04. It predicts a minimum gain specification of 1.33 to 1.57.*

registers can program the gain from 1.5 to 12.5 in 3% increments.

Projection of Manufacturing Specifications

In the manufacturing release of this IC, no reliable data was available to set the minimum gain specification (1.5 nominal) of the programmable gain circuitry shown in Fig. 2. This gain cell can be programmed to amplify small signals with a nominal gain of 1.5 to 12.5.

An inaccurate specification on the minimum gain would cause high parametric yield loss. The statistical simulation techniques described previously were carried out to project the gain distribution in a real-life manufacturing environment. For these simulations, 36 circuit elements were identified as random variables. The correlation coefficients of these variables were compiled from production data for the HP5 process. Specifically, the following intradie device correlations were accounted for:

- Correlations between resistors
- Correlations between transistor model parameters
- Correlations between resistors and transistor model parameters.

A 200-sample Monte Carlo simulation was carried out. The simulated minimum gain distribution is shown in Fig. 3. It projects a $\pm 3\sigma$ specification of 1.33 to 1.57. Measured production data for six months shows a distribution with a mean of 1.43 and a standard deviation of 0.034 (Fig. 4). The measured data projects a specification of 1.33 to 1.53. The simulated and manufacturing statistics are compared in Table I.

Statistical Simulation as a Diagnostic Tool

A second example of the power of this simulation technique illustrates its role as a diagnostic tool. The portion of the IC under study is the dc restore circuit, which level shifts the complementary high-frequency outputs to the ground level. A block diagram is shown in Fig. 5. From

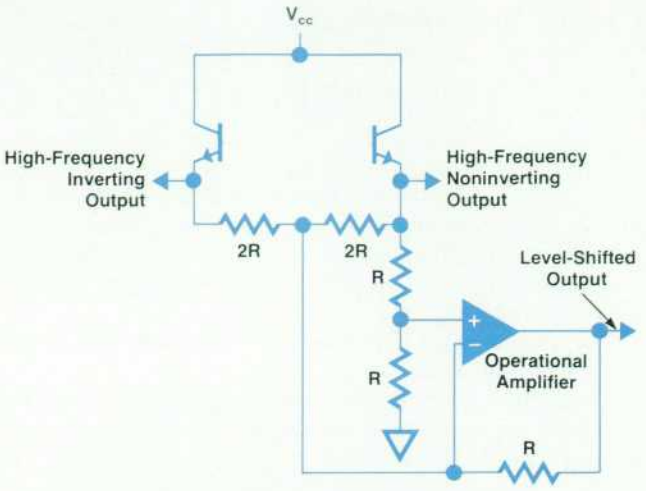

Fig. 5. *A portion of the integrated amplifier IC showing the operational amplifier and resistor bridge of the level shifting subcircuit. The op amp in this dc restore circuit had a large low-frequency output offset for which the simulation data did not match the production data, suggesting a process anomaly.*

Table I
Comparison of Simulated and Measured Minimum Gain Distributions

	Simulated	Measured
Mean	1.44	1.43
Standard Deviation	0.04	0.034
Specification	1.33-1.57	1.33-1.53

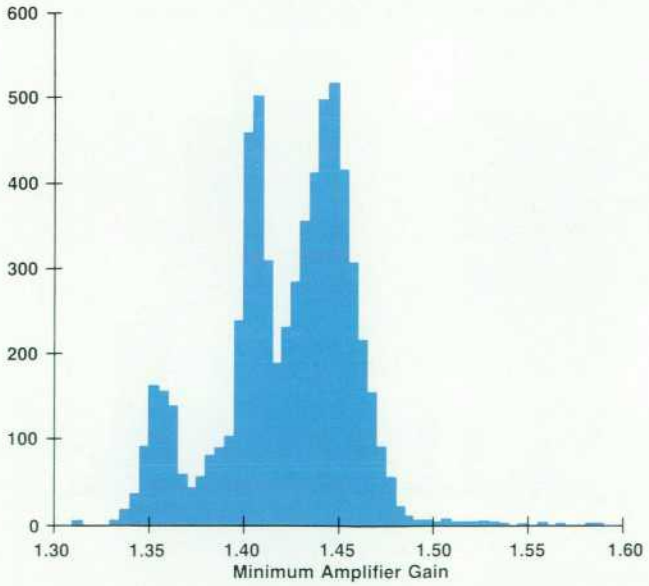

Fig. 4. *Six-month production data has a distribution with a mean of 1.43 and a standard deviation of 0.034. The minimum gain specification is 1.33 to 1.53.*

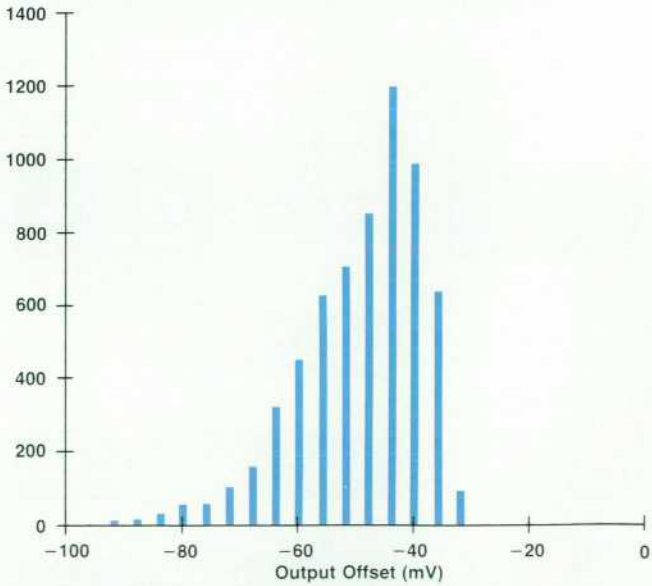

Fig. 6. *Distribution of the output offset of the op amp from production data. The mean is −49 mV and the standard deviation is 11 mV.*

production data, the low-frequency output offset voltage of the op amp had been observed to be large. The op amp output offset voltage is defined as the output voltage of the op amp when the two high-frequency outputs (inverting and noninverting) are equal. Under balanced conditions, the output offset should be close to zero. It was not known what the standard deviation caused by process latitudes should be. Fig. 6 shows a typical distribution of this parameter from six months of production data. It has a mean of −49 mV and a standard deviation of 11 mV.

The op amp circuitry has 22 random variables, of which 12 are highly matched resistors and 10 are the transistor model parameters. Correlated simulations were carried out as for the first example. A 200-sample simulation revealed the distribution of the offset voltage to have a mean of 11 mV and a standard deviation of 3.4 mV. Such a large discrepancy between the manufactured and simulated distributions suggests some hidden process anomaly that has not been discovered.

Subsequently, the process defect that caused this wide distribution of the output was identified. The circuit was redesigned to desensitize it to the process defect. The distribution from one wafer after redesign is compared to the simulated distribution in Fig. 7. The redesigned circuit shows a mean of 6 mV and a standard deviation of 4.8 mV. The simulated values are close to the initial production data. The slight discrepancies of the standard deviations can be accounted for by a variety of second-order effects that were not included in these simulations, most notably variations in metal resistivity and metal-to-metal contact resistance.

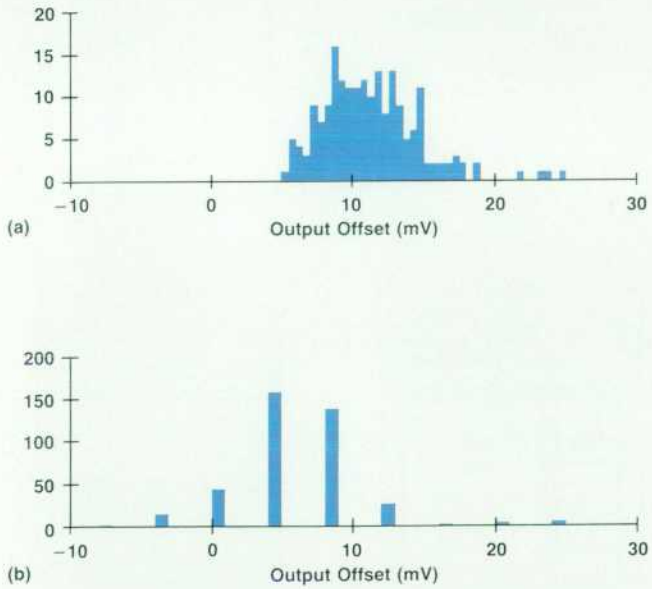

Fig. 7. *(a) The distribution of the output offset voltage of the op amp from 200 correlated simulations has a mean of 11 mV and a standard deviation of 3.4 mV, very different from the production data shown in Fig. 6. (b) The distribution from one production wafer after redesign has a mean of 6 mV and a standard deviation of 4.8 mV, more closely matching the simulation data.*

Conclusions

This statistical circuit simulation study has demonstrated the accuracy of this technique in projecting circuit performance distributions in manufacturing. The technique also has a valuable role as a diagnostic tool for troubleshooting process problems. Despite some assumptions used both in the underlying principal component analysis theory and the device modeling, these simulations are accurate enough to be a practical CAD tool in product development.

It is hoped that this approach to design for manufacturability, through synergism of volume production data with design simulation tooling as exemplified by this simulation study, will be a significant contribution to manufacturing technology.

Acknowledgments

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System Level Air Flow Analysis for a Computer System Processing Unit

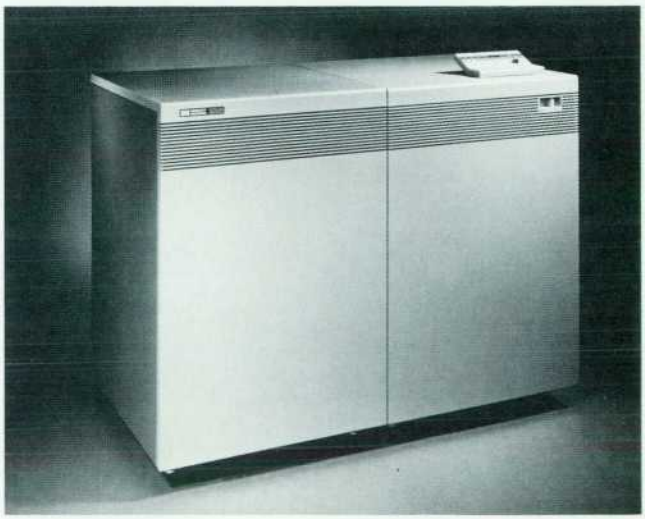
Numerical simulation of particle traces using finite element modeling and supercomputers gives a good qualitative picture of air flow features. Computed velocity profiles and pressure drops have reasonably good accuracy.

by Vivek Mansingh and Kent P. Misegades

STEADY, VISCOUS, THREE-DIMENSIONAL AIR FLOW within a computer system processing unit has been analyzed using finite element modeling. The objective of the study was to investigate the effectiveness of finite element modeling in predicting the air flow characteristics within a computer. A full-scale three-dimensional finite element model of an HP 9000 Model 850 computer was created using FIDAP, the finite element code from Fluid Dynamics International. This model consisted of over 60,000 nodes and over 40,000 8-node brick elements. Extensive computations were carried out using CRAY Y-MP supercomputers. General flow characteristics, including velocity profiles and pressure drop across the system, were computed. Numerically calculated particle traces were recorded using video equipment. It was found that numerical simulation of particle traces can show good qualitative features of the flow through the system and the modeling results of velocity profiles through the boards and the system pressure drop have reasonably good accuracy.

Project Objective

For the thermal management of air-cooled computers, the key air flow parameters to be determined are the air



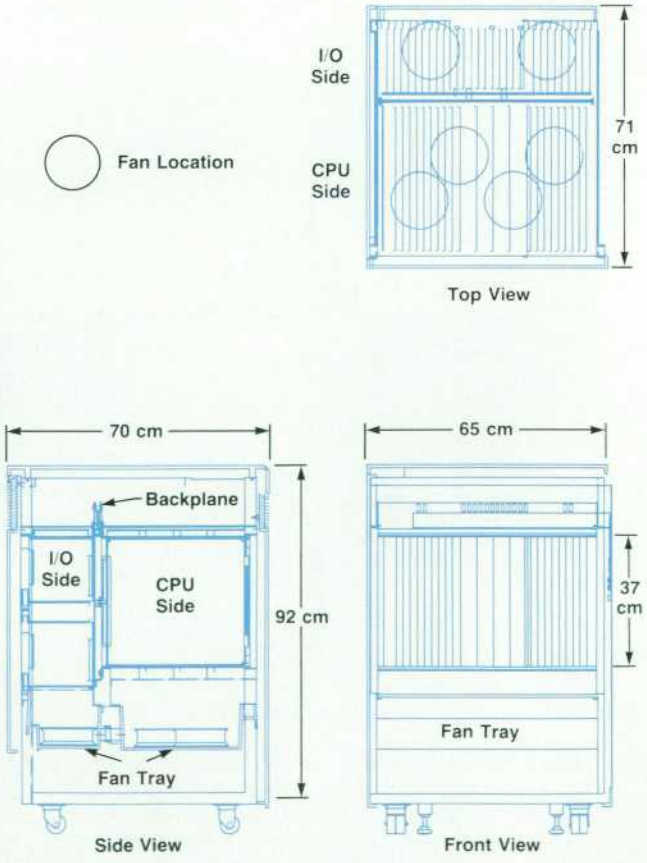


Fig. 1. *HP 9000 Model 850 computer system processing unit (right side of computer in photo). There are six fans.*

velocities in the computer cabinet and the pressure drop across the system. The air velocity flow characteristics in the system help in designing the system layout at the board and component level while the system pressure drop forms the basis for selecting air movers. Thermal management at the component level also requires the knowledge of board and component level air flow characteristics.

Traditionally, pressure drop and flow characteristics within a computer cabinet have been experimentally measured on prototypes of the machines. Unfortunately, an accurate prototype can only be available when all the components of a system have been designed. This typically happens only towards the end of a design effort. Therefore, the flow characteristics and the system pressure drop can be accurately measured only after almost all the components of the system have already been designed. If for some reason the pressure drop is found to be excessive or the air flow characteristics are found to be different than expected, major design changes may have to be made at the end of the design cycle, resulting in serious product modifications and delays. Furthermore, experimental measurements in a prototype are both difficult and expensive in terms of human effort.

It would be advantageous to have modeling tools that can predict these air flow characteristics early in the design process. A model could also easily simulate effects of high altitude, zero gravity, and other conditions. The objective of this study was to investigate the effectiveness of finite element modeling in predicting the air flow and pressure drop characteristics within a computer.

Model Development

As mentioned earlier, a full-scale model of an air-cooled HP 9000 Model 850 computer system processing unit (SPU) was created. A photograph and a drawing of a Model 850 SPU are shown in Fig. 1. A Model 850 SPU is approximately 1 m high, 0.7 m wide, and 0.7 m deep. It has four processor boards and several other memory and I/O boards. The backplane essentially divides the cabinet into two halves: the CPU (central processing unit) side and the I/O side. It has six tube axial fans for cooling, which operate in the suction mode. Four of these fans are for the CPU side and two are for the I/O side. The air inlet is at the top and the outlet is at the bottom. Detailed mechanical drawings showing locations and dimensions of the structural components, printed circuit boards, suction fans, flow inlets, and flow outlets were used to create the full-scale model of the system using FIDAP's preprocessor FIPREP and mesh generator FIMESH. The full model was divided into smaller finite elements using 8-node brick elements. Fig. 2 gives a view of the final mesh, consisting of 60,507 nodes and 48,600 elements.

From the outset, it was recognized that detailed three-dimensional modeling from the system level to the component level, that is, from the overall dimensions of the cabinet down to the smallest component on a board, was impossible, both from a modeling standpoint and because of computation time requirements. For instance, we estimated that simulating the flow through just one of the CPU boards having a number of RAM chips, PGAs, CPU chips and multifinned heat sinks would require a mesh of approximately 60,000 to 100,000 elements and a run time of more than 10 CPU hours. Therefore, it was not possible to model every single component in the system. Since the main focus for this project was on system level characteristics, a component level simplification in the geometry was made. To model the components on the boards, it was

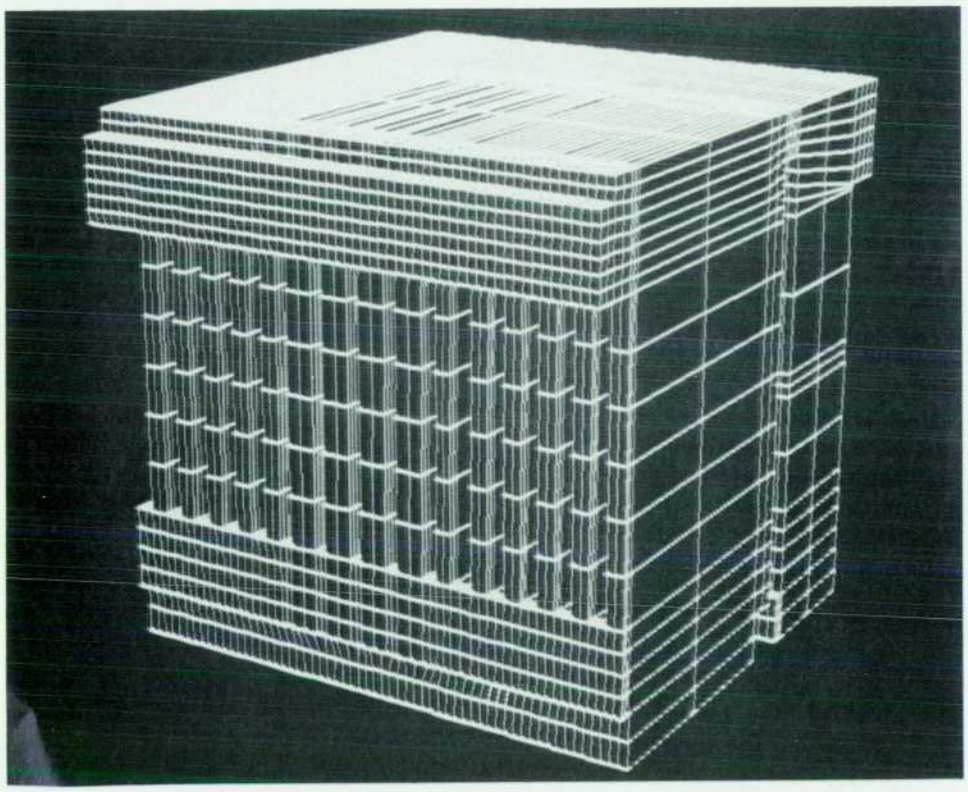


Fig. 2. *A view of the finite element mesh for simulation of the air flow in an HP 9000 Model 850 SPU. The complete mesh consists of 60,507 nodes and 48,600 8-node brick elements.*

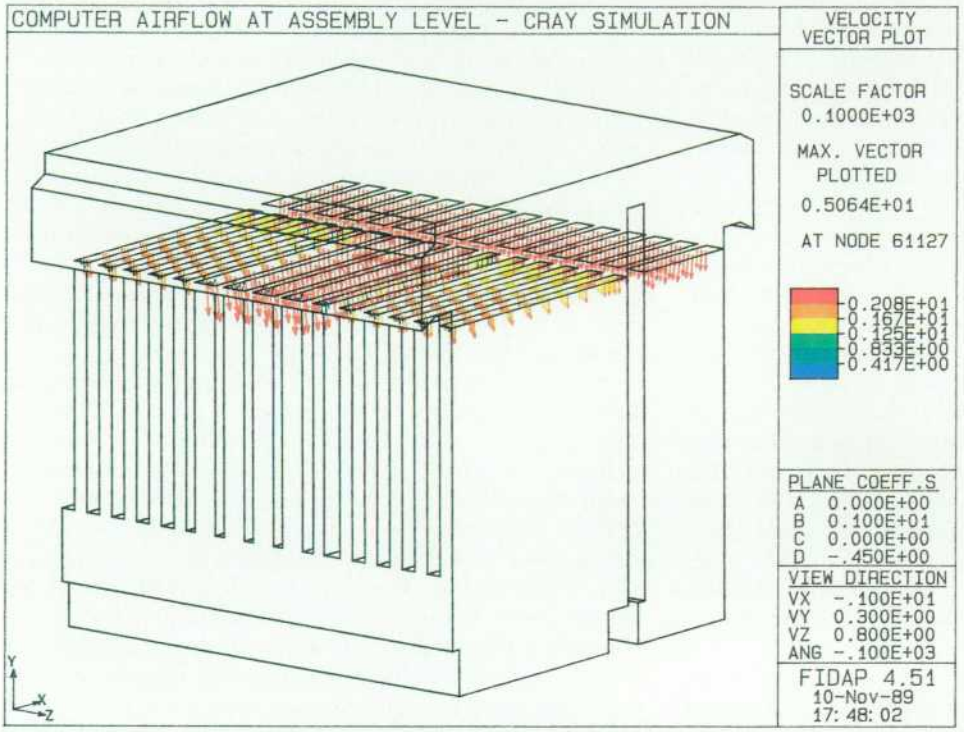


Fig. 3. *Computed flow velocities in the X-Z plane at the entrance to the printed circuit boards.*

assumed that between any two printed circuit boards, a certain percentage of the flow passage was blocked by components. Based on good engineering judgment, for the four CPU printed circuit boards the blockage was assumed to represent 30% of the volume between two adjacent boards, whereas for all the other boards the blockage was assumed to represent 50% of the volume between adjacent boards. Flow deflection vanes at the air inlet of the cabinet were included in the model as infinitely thin plates at the same angle as the actual vanes.

Although the computational effort required to generate this three-dimensional model was moderate, it took approximately 1½ engineer-months to create the model beginning from mechanical drawings. It is also important to note that the use of computer graphics was essential to the successful creation of this mesh, visual analysis of the mesh

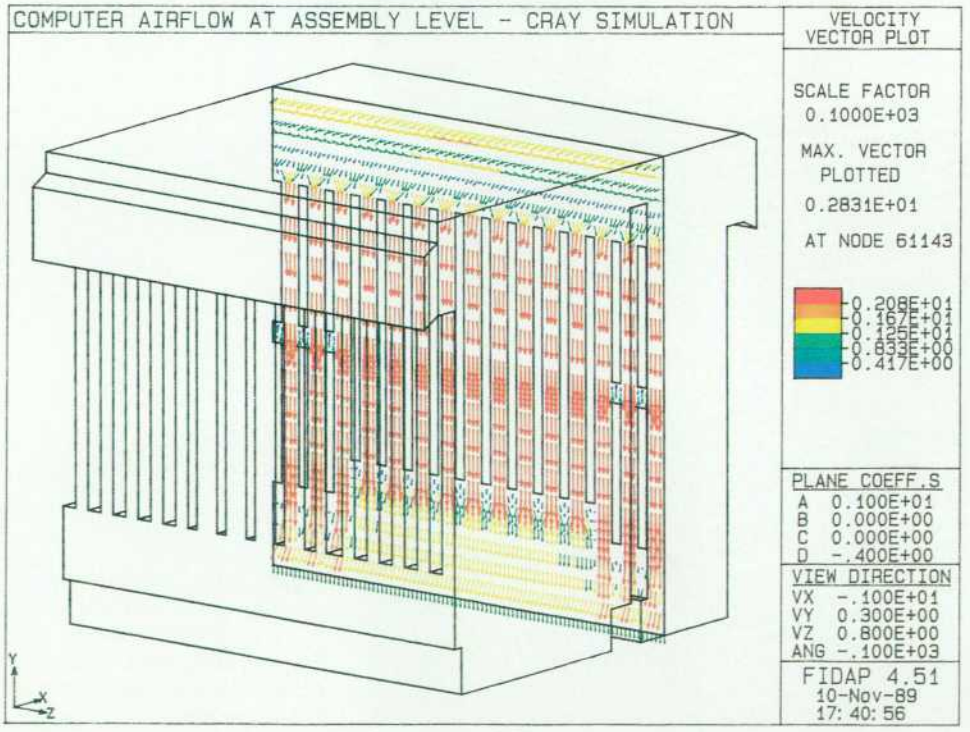


Fig. 4. *Computed flow velocities in the Y-Z plane through the printed circuit boards.*

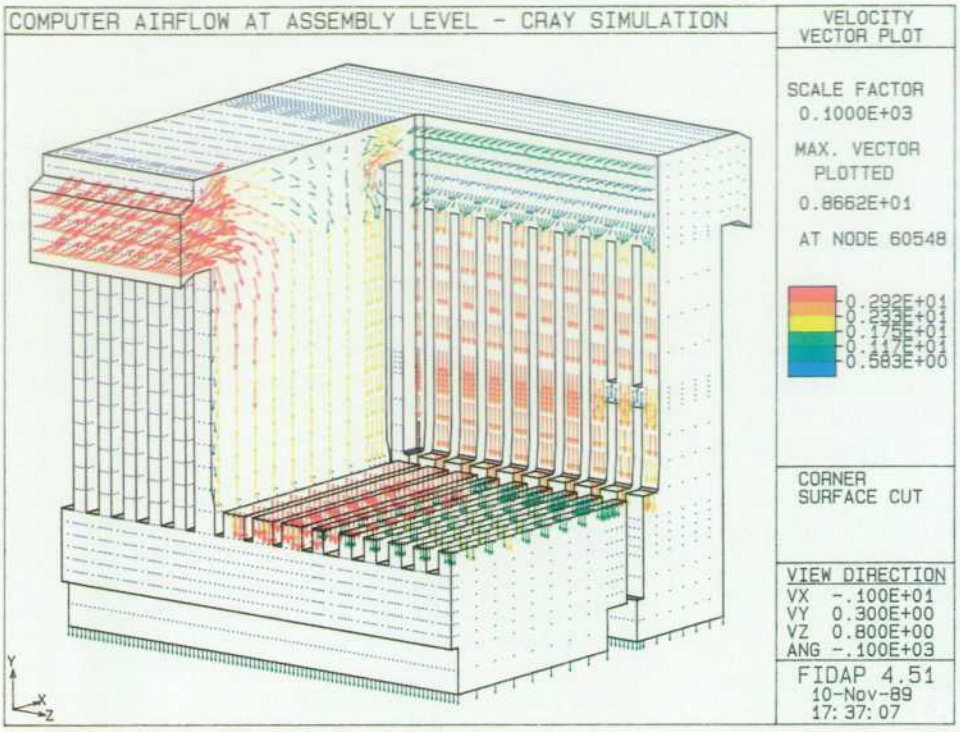


Fig. 5. *Computed flow velocities through the system.*

generator's results being the only good means of checking progress. For this, both FIDAP's postprocessor FDPOST and Cray's Multi-Purpose Graphics System MPGS were used. All computations, including graphics, were performed on CRAY Y-MP supercomputer systems.

Boundary Conditions

The physical problem modeled was three-dimensional, steady, viscous, laminar, isothermal flow. Because the velocity through the system was of the order of 2 m/s and the length scales of the components were small, the flow was assumed to be laminar. The flow was assumed to be isothermal because the main focus of the problem was the

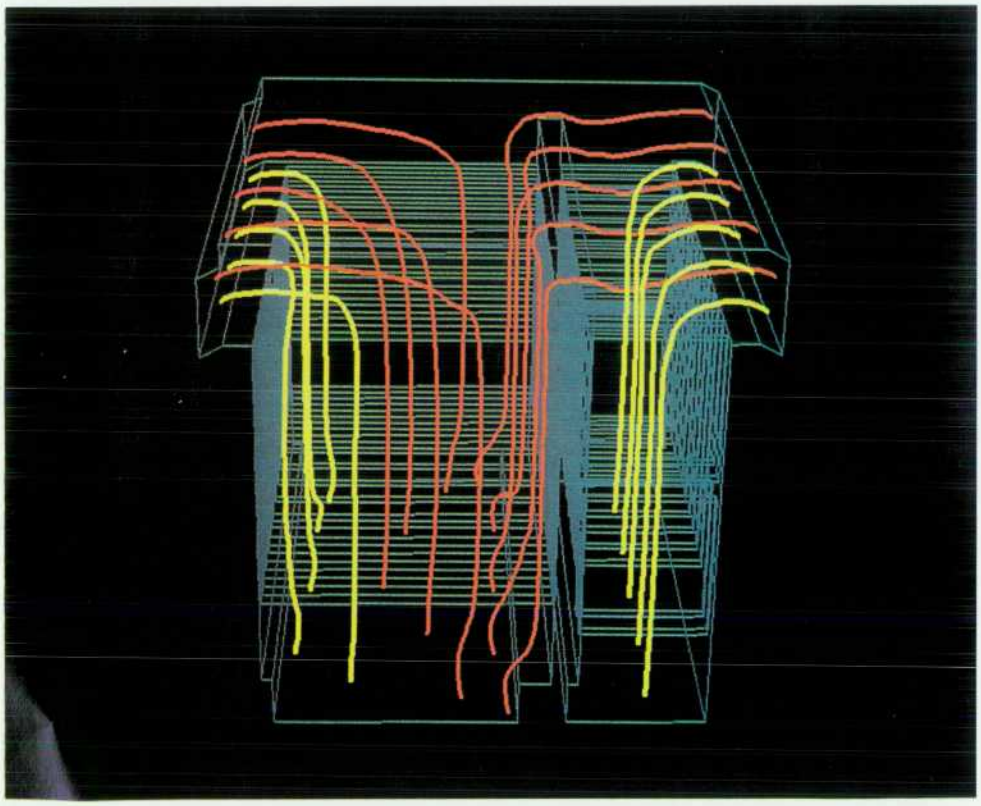


Fig. 6. *Animation of simulated particle traces representing the air flow.*

fluid flow characteristics.

On all solid surfaces of both physical and blocked regions, a no-slip velocity boundary condition was specified. At the two air flow entrances on the top front and back of the cabinet, no boundary conditions were set. For the air outlet at the bottom of the cabinet, a constant-velocity boundary condition was defined. However, for the outlet boundary condition, not enough information was available initially. The flow rate produced by a fan is dependent on the pressure drop it experiences. Flow rates are given in tabular or graphical form as a function of pressure drop. The data used in this work was for the fans running at 60 Hz at sea level. Since we did not know the pressure drop of the system at the outset, it was not possible to know the fan flow rate that would define the air exit boundary condition. To get around this problem, the following iterative procedure was used:

1. An initial fan flow rate was guessed.
2. For this given fan flow rate, the flow field including the pressure drop was calculated based on the uniform exit velocity across the exit area that would result in the same volumetric flow rate as produced by six fans.
3. For this computed pressure drop, the corresponding flow rate from the fan manufacturer's performance curve was found.
4. An average of this new flow rate and the previously guessed flow rate was used to calculate the exit velocities, which were used as new boundary conditions for the next computation.
5. This procedure was repeated until the guessed flow rate produced the corresponding pressure drop according to the fan curves.

Computations

The three-dimensional Navier-Stokes equations of motion[1] were solved in the nondimensional form. The solution technique used was the segregated method.[2] A separate linear system was solved for each of the four degrees of freedom—three velocity components and pressure. Relaxation factors[2] used for the four degrees of freedom were 0.8, 0.8, 0.8 for the three velocity components and 0.0 for pressure. To improve the accuracy and stability of the solution, an upwinding factor[2] of 1.0 was used for all degrees of freedom for all computations because high velocity gradients were expected in the coarse mesh regions.

Starting from an initial linear Stokes flow solution, the problem was run for five iterations using the segregated solver, resulting in the following solution or convergence errors for the four degrees of freedom:

- X Velocity: 0.0084
- Y Velocity: 0.0074
- Z Velocity: 0.0038
- Pressure: 0.021.

The *FIDAP User's Manual* recommends that these values be driven to 0.001 when using the segregated solver. However, we were not able to converge to values lower than these even though several other values of relaxation and upwinding parameters were tried.

After the initial five-iteration solution, a new fan flow rate was guessed and a second run was made. The solution was said to have converged when the pressure error was less than or equal to that of the first run, 0.021. The results of this iterative procedure are given below:

Typical FIDAP Run

Run	Number of Iterations	Fan cfm Guessed	Pressure Error	Pressure Drop Computed	Fan cfm Actual
1	5	100	0.021	0.46 in H_2O	70
2	7	85	0.016	0.40 in H_2O	90

In this typical example, 12 iterations were required to find a value of fan flow rate within 10% of that actually supplied by the fan. Given that other simplifications in the model had been made, it was felt that this level of convergence and accuracy was adequate.

On the CRAY Y-MP supercomputer, 10 hours of CPU time were required to perform the 12 solution iterations needed. Memory needed was 4.0M words of main memory and 87M words of secondary memory or scratch memory. For scratch memory, a CRAY SSD (solid-state storage device) was used. This reduced an otherwise substantial I/O wait time penalty for disc memory devices to a small fraction of the total run time.

Numerical Results

As mentioned earlier, general flow characteristics including the velocity profile and the pressure drop across the system were computed. Some typical pictures of the flow velocities through the system are shown in Figs. 3, 4, and 5. These illustrate well the qualitative features of the flow entering the CPU side and the I/O side at the top section, turning and going through the printed circuit boards, and exiting the fan outlet region. An interesting aspect of the results is that a substantial portion of the flow entering the I/O side or the rear of the cabinet actually passes over the backplane obstruction in the top section and flows to the CPU side at the front of the cabinet. It can also be seen that the velocities are low at the entrance, increase between board slots and then decrease again at the exit of the board slots. The air velocities are higher in the four CPU board slots than in the memory and I/O board slots and are in the range of about 1 to 2.75 m/s.

As mentioned earlier, simulated particle paths or traces were recorded on video. The traces represent the path that a massless particle would take through the computer cabinet if released at various locations along the inlet planes. Such traces are very useful in giving a qualitative representation of the three-dimensional complex flow field. Using MPGS, the Multi-Purpose Graphics System from Cray Research, these traces were animated to show the details of the flow. The animation very clearly shows the cross flow of air from the I/O side of the cabinet to the CPU side and other complex features of the flow. A typical picture of particle simulation is shown in Fig. 6.

Experimental Results

Experimental measurements of the air velocities were carried out on an actual system with the help of a hot-wire anemometer. The cabinet walls and some of the boards were modified so that the hot wire could be inserted into the cabinet at the desired locations. Velocity profiles were

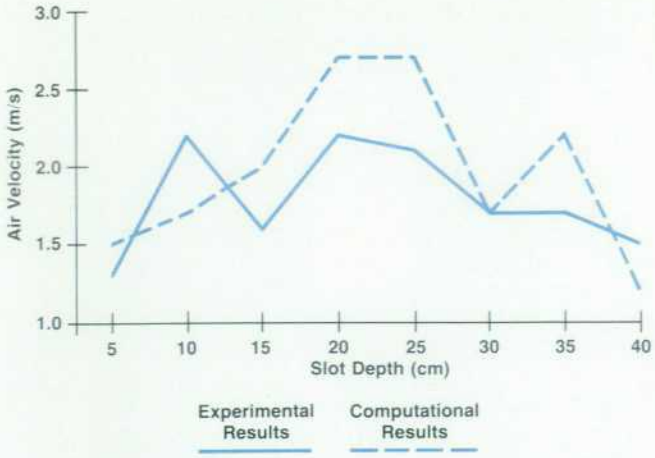


Fig. 7. *Computed and experimental air velocities in CPU board slot 0 at the middle of the board.*

measured in the CPU and I/O board region across the boards. A typical velocity profile measured in CPU board slot 0 at the middle of the board is shown in Fig. 7. The slot depth (X in Fig. 3), is plotted on the x axis while the respective velocities are shown on the y axis. It can be seen that the air velocities are in the range of 1.25 m/s to 2.25 m/s. The velocities are about 1.5 m/s at both ends of the board, with the highest velocities of about 2.25 m/s in the middle of the board. One of the reasons for the nonuniformity in the velocity profile is the presence of various components (chips, heat sinks, etc.) on the board.

A comparison of the numerical results with the experimental results is also shown in Fig. 7. The numerical results predict higher velocities in the center and lower velocities near the ends than were actually measured. However, the range of velocities is about 1.5 m/s to 2.75 m/s, which is relatively close to that measured experimentally. It should be noted that in the numerical simulations, the board components were modeled as blockage to the flow, whereas in the experiments, the boards had actual components on them.

Conclusions

Steady, viscous, three-dimensional air flow within a computer SPU has been analyzed using finite element modeling. General flow characteristics including velocity profiles and pressure drop across the system were computed. Numerically simulated particle traces were recorded using video equipment. It was found that numerical simulation of particle traces can show good qualitative features of the flow through the system. The particle traces show some extremely interesting flow characteristics that could not have been known easily otherwise. The computed velocity profiles through the boards and the computed system pressure drop have reasonably good accuracy. Modeling predicted the air velocities through the CPU board slots to be about 1.5 m/s to 2.75 m/s whereas the experimental measurements showed about 1.25 m/s to 2.25 m/s. However, finite element modeling can be relatively expensive in terms of computation time.

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