I/O WALL: INTERACTION DESIGN THROUGH ASSOCIATIVE PARAMETRIC MODELING

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0. Abstract

While the ‘disappearing computer’ offers a compelling vision for the future of human-computer interaction, its reality depends very much on design decisions made at the level of the architectural detail. This case study outlines a series of design proposals developed to explore the formal and tectonic implications of embedding computer hardware and functionality in building interiors. Students in two studios at the Southern California Institute of Technology were asked to design a wall of shelves capable of detecting and displaying patterns in the use of the shelves and surrounding spaces over time. The goal in both studios was to imagine new forms for the building interior based on the dimensions, range, optimal spacing, and other characteristics of the embedded computer hardware (sensors, microprocessors, and LED’s), as well as on the interactive potential of the wall. Each student project resulted in a prototype interactive system which is parametrically defined for fabrication and for future reconfiguration. The design proposals were evaluated according to a set of criteria that we established to assess the effectiveness of the parametric system and the success of the form as a mapping of the interactive capabilities of the building interface.

1. Introduction

1.1 Building Interfaces

The integration of computer functionality in the built environment is already becoming commonplace, both in the home and in contemporary institutional buildings. Networks of sensors are used to monitor temperature, humidity, and carbon dioxide levels in the air; solar radiation on the facade; and the presence of building occupants. This information can then be used to optimize the effectiveness and efficiency of building environmental systems, to time the raising and lowering of operable sunshades, and to automatically open doors as people approach them. Standards are being developed for wireless [1] and wired [2] communication between controllers and input/output (I/O) devices such as sensors, automated building components, and information displays.

The integration of I/O devices in the building has provided architects with a new range of tectonic expression, particularly in the articulation of output devices and the temporal variation that they can bring to the building interior and the building envelope. The 1988 Institut du Monde Arabe building by Jean Nouvel in Paris is one early example of a computer output device – the motor-controlled diaphragm sunshades on the façade – that is enabled to become a highly expressive architectural element. The tectonic expression of the motorized diaphragm and its dynamic response to seasonal and daily changes in the environment is both a reinterpretation of a traditional element in Islamic architecture (the mashrabiya), and an iconic representation of the building and of its function as a center of Islamic culture [3].

Many other buildings since the Institut du Monde Arabe have explored this capacity of computer output devices to provide a dynamic tectonic expression of computer-controlled functionality. The types of output devices used have ranged from motorized façade elements (the transparent glass louvers of Jean Nouvel’s 2004 Torre Agbar Headquarters) to
the large-scale display of computer data (the illuminated and "pixelated" facades of the Torre Ágbar Headquarters, Toyo Ito’s 1986 Tower of Winds or Peter Cook and Colin Fournier’s 2003 Kunsthaus Graz). In each of these cases, the output devices serve a functional purpose and also a symbolic role as an expressive representation of the computer functionality embedded in the building.

It is worth noting that while many projects have explored the expressive potential of computer output devices in architecture, few have addressed the tectonic implications of computer input devices (sensors) and of the network itself. The Media House Project [4] notably proposed an integration of the building’s power and data network into wooden structural elements, an idea that was substantiated by the use of Internet 0 [5], a simple communication protocol that provides an inexpensive and efficient means of assuring interoperability between networked building components and building systems. The project’s close integration of building structure and building data was functional in that supported interoperability and the use of the building itself as an interface to computer functionality. It was also a rhetorical expression of the idea that the building itself has become a computer, and the various components of the building are interfaces to the functionality afforded by that computer.

1.2 Associative Parametric Modeling
The I/O Wall project was conceived as an exploration of the tectonic implications of the building as computer, the idea that computer inputs and outputs can become an integral aspect of the tectonic expression of the building. In particular, we were interested in investigating the specific affordances offered by associative parametric design techniques to describe the relation between interactive functionality and construction, at the scale of the building and of the detail. We saw the I/O Wall project as a means of identifying the areas in which parametric methods could be used to effectively address the challenges of integrating dynamic computer functionality in the building.

Associative parametric design tools offer the possibility of pre-rationalized constraint-based design, a process in which a design is advanced through the identification and adjustment of specific quantifiable elements of the project [6, 7]. In this case the parametric method was chosen for several reasons. First, the design of architectural elements with embedded computing involves the coordination of multiple constraints (such as sensor ranges and the physical dimensions of computer components) which can be integrated into the digital model as parameters. Second, the parametric method was chosen for its potential to radicalize individual design. The desired aesthetic for the project involved uniqueness and organicity, qualities that required us to go beyond standardized off the shelf assemblies. Using parametric design (PD), a large number of solution spaces can be evaluated not only in terms of the pre-rationalized program requirements but also the stakeholders’ subjective design sensibilities.

The project was also used to explore organicity as a deliberate design agenda, associating freeness of interaction with non-uniform freeness of surface and volumetric articulation. In other words, we were interested in the potential of organic, non-uniform structures to express the dynamic and interactive functionality inherent in a building with embedded computer interfaces, resulting in both a ‘legibility’ of the interactive potential and in a tectonic expression of the computer input and output devices. Our hypothesis was that by constructing abstract reconfigurable models, we would be able to tune the tectonic expression during the design process, resulting in a functional and expressive interactive architecture.

For 3D modeling of these project variations we used the

Gehry Technologies (GT) Digital Project (DP) platform, an associative parametric CAD environment based on the CATIA software platform. AutoCAD and 3D Studio Max are also used but were intentionally not the predominant design environment.

1.3 Ubiquitous Computing
A principal goal of Ubiquitous Computing is the distribution of computer functionality among everyday objects and environments, allowing interaction with computers to become associated with intuitive, uncomplicated activities and gestures [8]. By embedding inputs (sensors) and outputs (displays, motors) in the world of things, Ubiquitous Computing envisions a future in which the computer will ultimately disappear as a focus of attention [9]. In this vision, interaction with the ‘embodied computer’ is enhanced by the diverse material and formal qualities of the distributed computer interfaces.

One benefit of embedding computer outputs in the built environment is the presentation of information that can be processed in the background of one’s awareness, without disrupting the foreground tasks in which one is currently engaged [10]. Such ‘ambient’ displays can take the form of a texture applied to familiar architectural surfaces such as the wall or ceiling, a texture which is unobtrusive and yet capable of conveying information through subtle transformations. The display becomes an interactive wallpaper [11] that fades into the background when not in use, and only occasionally becomes the object of one’s full attention.

The use of information visualization at the scale of the room has been explored in numerous projects at the intersection of ubiquitous computing and information visualization [12, 13]. The rapid development of new architectural materials in recent years has offered many new opportunities for creating building surfaces that are capable of performing multiple functions, including sensing and display. In parallel, new display technologies are being developed that permit low-energy, non-emissive display over a large surface [14, 15].

Another benefit of embedding computers in the built environment is the potential to track movement and physical activity using sensors as computer input devices [16]. Transactions with information on the computer can easily be tracked, searched, and represented visually; embedded computers can provide an interface for tracking, searching, and representing visually interactions with physical objects such as books, equipment, and workspaces.

2.0 The I/O Wall Project
The I/O Wall project began as a collaboration between the Media and Design Lab at the École Polytechnique Fédérale de Lausanne (EPFL), and faculty and students at the Southern California Institute of Architecture (SCI-Arc). The site for the project was the lab space of the Media and Design Lab, a new academic research group in digital media, interactive architecture and digital fabrication methods. One wall of the lab space consists entirely of 4-meter high windows opening onto a dramatic atrium, an important public space within the building and the principal public face of the lab. From the beginning of the project, it was anticipated that the I/O Wall would address this public interior façade as a means of communicating to colleagues and passers-by the focus of the lab and its vision for the future.
The project involved the design and construction of a free-standing wall with integrated storage, display, workstations, and equipment stations (alcoves for a printer, laser cutter, and CNC milling machine). Consistent with the research focus of the Media and Design Lab, the wall was conceived as an infrastructural component of the creative office of the future: assuming that the workspace of the near future will need to gracefully accommodate integrated sensing and information display, as well as personal fabrication equipment.

The I/O Wall was also conceived as an interface to computer functionality, consisting of inputs (sensors) and outputs (displays). The project proposed a wall of shelves that records patterns of activity related to the space, the wall, and the objects stored in the shelves. A display interface presents the information recorded by the sensors in real time, and as a record of past activity. In this way, the wall stores and presents a memory of actions that have taken place in the space.

2.1 Project Team
The core project team included: Jeffrey Huang, professor and lab director of the Media and Design Lab; Mark Meagher, a doctoral candidate at the Media and Design Lab; and David Gerber, faculty at SCI-Arc. The project participants included two groups of David Gerber’s undergraduate and graduate architecture students during 2006 and 2007. The student participants were Noriaiki Hanaoka, Chikara Inamura, Lionel Lambourn, Alex Pena, Peter Dang, Demko Dean, and Jun Yu.

2.2 Project Dates and Duration
The project was initiated using seed funding provided by the Media and Design Lab in May 2006. During the summer of 2006 David Gerber worked with a group of his students to develop a series of design iterations (drawings and scale models) which were exhibited at EPFL and SCI-Arc in September 2006. Following an intensive design charrette at the EPFL in November 2006, a new group of SCI-Arc students addressed the I/O Wall brief with another series of designs, based on the work of the previous student group and the revised brief resulting from the November 2006 charrette. A third group of students continued the spatial and formal refinement of the I/O Wall during the spring and summer of 2007.

2.3 Challenge
The project was premised on a belief that the integration of computer functionality in the built environment introduces new opportunities for architectural expression. It was our goal to produce prototypes that would illustrate the expressive potential of embedded computer input and output devices in building interiors. We investigated the hypothesis that associative parametric modelling would provide unique affordances for effectively addressing the challenges of integrating dynamic computer functionality in the building.

The challenges specifically addressed in the project were two-fold: a) the symbolic representation of the interactive potential of the interface; and b) the elegant accommodation of multiple constraints imposed by the embedded computer hardware, such as sensor ranges and the physical dimensions of the components and cabling.

The first challenge was addressed through the use of associative parametric modelling to generate multiple design iterations, each of which was evaluated in terms of its potential to express the interactive potential of the computer interfaces embedded in the wall. For reasons related to usability and privacy, we decided that the design of the wall should express the fact that a network of sensors has been embedded, and should provide an indication of the types of interaction that are possible. While it is often necessary (and beneficial) to conceal computer interfaces within traditional building interfaces like the door, the window, the ceiling, or wall, concern for usability requires that these interfaces communicate the range of interaction that is possible and the information that influences the behaviour of the interface.

In addition to these pragmatic considerations, the ‘organicity’ of the wall’s form was explored as an aesthetic means of communicating the wall’s interactive functionality. We were interested to see whether parametric modelling could be effectively used to ‘tune’ the design for the expression of a particular idea. Although the association of fluid form with the dynamic and changeable qualities of interactive interfaces can easily become a cliché, we chose to use this association as one tool for expressing the idea of the building as computer.

The second challenge was addressed through the use of associative parametric modelling to include the constraints of sensor dimensions and optimal ranges as well as the LED displays in order to develop a tectonic expression of the embedded computer interfaces. The students were asked to include these constraints in their model, and to develop a design that included the sensors and LED’s as tectonic elements which
influence the overall constructional logic of the wall. The goal in this aspect of the project was not simply to conceal the hardware, but rather to use the hardware and its functional constraints as a starting point for designing the system.

2.4 Solution

2.4.1 Interaction Design and Technology
The I/O Wall was conceived as a multi-purpose surface designed to support a range of functions (storage, workstations, equipment stations), and the wall’s interactive component was designed to track and represent patterns of use related to these functions. Infrared sensors were chosen as a means of detecting the presence of people along the surface of the wall, providing a rough understanding of the frequency of use of each of the functions embedded along the wall’s perimeter. Radio frequency identification (RFID) readers were selected as a means of keeping track of the presence or absence of objects stored in the shelves: by attaching a tiny RFID tag to each object, it became possible to identify the objects individually and to know where they were located in the shelves.

Figure 3: The computer hardware embedded in each node: (A) RFID reader; (B) I/O board, with Zigbee wireless module and LED matrix; and (C) infrared sensor. The model shows the hardware dimensions and their ranges, as these were approximated for use in the parametric model.

The basic unit, or ‘node’ in the computer network of the wall consisted of one infrared sensor, one RFID reader, one I/O board for reading the input from both sensors, one wireless communication module, and a 6-LED matrix for display (Figure 3). Each of the nodes communicated wirelessly with the base station, a unit that receives and transmits data via serial connection to a server. The collection and storage of sensor data was facilitated by the open source Global Sensor Network software [17], a middleware that handles communication with the sensor nodes and the writing of sensor data to a web-accessible MySQL database. The sensor data was received by the server every second, processed in the server, and then sent back to the sensor nodes as instructions for the illumination of the LED’s.

In order to determine the functional constraints of the computer inputs and outputs, we built a small prototype of the sensing, actuation and control systems using off-the-shelf hardware and software (Figure 4). We used a SHARP infrared sensor (model GP2Y0A02YK) and an RFID reader from APSX (model RW-310), selected for their range and low cost. The I/O board used was the Arduino [1], an open source hardware platform for quick prototyping, and the wireless communication module was a Maxstream Zigbee [18] RF module. The LED matrix was implemented only as a static prototype, not actually connected to the sensor network, using off-the-shelf 6-LED matrices and a DMX control interface.

Figure 4: The Xbee wireless basestation, and LED matrix.

For the prototype we built four sensor nodes, and determined through experience the functional properties and limitations of each of the hardware components. The nodes were installed on a standard bookshelf in the lab space, and activity data was gathered over the course of one week. Based on this data the design of the nodes was revised: for example the SHARP GP2Y0A02YK was substituted for the original IR sensor because of its narrower field of vision. Within the time constraints of the project, we did not succeed in setting up the wireless network and chose instead to use a wired connection between the sensor nodes and the server.

Based on the information gathered from the prototype, we provided the students with a set of constraints and guidelines for the integration of the sensor nodes in their projects. We summarized dimensions, ranges, and interactive functionality as well as other details such as power consumption, heat production, required cabling, and materials. It was then up to each student to decide how to integrate the nodes into their design; one project that developed a promising strategy for functionally incorporating the nodes and expressing the presence of the computer hardware is shown in Figure 5.

Figure 5: Location of sensor nodes on the I/O wall (project materials courtesy of author’s 2006 SCI-Arc student June Yu).

2.4.4 Student Projects
These projects present the use of associative parametric design with real world constraints: context, economics, ergonomics, and finally technical integration of the I/O devices. The opportunity was to investigate the design paradigm for rapid design variation and the incorporation of the complexities of sensing, visualization, and tracking technologies in conjunction with that of formal design. More advanced features of associative parametric design were also incorporated, including the automation of smart object instantiation and the extraction of constructible information for examples. Numerous formal strategies were used from point and smart
<table>
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| 1. Nori         | ![Image]         | driving surface and point instantiation system  
parametrization is based on simple four point input basis | The form is constrained to the properties of a deformed flat sheet material such as molded plywood.  
The intersection points do not anticipate the integration of sensors, LEDs, and associated wiring at this stage of the design, and could not easily be adapted for this purpose. | Provides horizontal surfaces for shelving and workstations.  
Does not provide adequate detailing for fabricating using an opaque material. | |
| 2. Chikara      | ![Image]         | Constructed from the aggregation of a smart component into a variable surface.  
Exhibits a wide range of productive design variation from both internal and external parametrizations. | The component is pre-rationalized and constrained to exhibit no undercuts for 3 axis milling.  
Although there is no articulation of the sensors, LEDs, and wiring at this stage of the design, the intersection points could be adapted to accommodate the necessary hardware. | The system provides shelving and work surfaces, with the drawback that few of these surfaces are horizontal. | |
| 3. Jun Yu       | ![Image]         | Uses a driving surface skeleton to manipulate the density of nodal points, which serve as the abstract geometry for instantiation of smart components.  
The design engine is built of two walls with a gap in between. | The two part smart component is constrained to exhibit no undercuts and was conceptually prototyped from unique molds constructed from 3 axis milling and tooling.  
Because the smart component consists of a milled nodal, it can easily be adapted to accommodate the hardware for sensing and actuation (LED’s). | Abundant horizontal surfaces are ideal for shelving and display.  
Workstations could easily be integrated into the system. | |
| 4. David        | ![Image]         | Uses a driving surface skeleton to manipulate nodal points, which define the intersection of planar horizontal and vertical members. | The system is designed as a pre-rationalization of flat sheet material with automated reconfigurable nothing for self assembly.  
The most pragmatic project in terms of fabrication. | The flat planar material (milled plywood) provides no exhibit affinities for concealment of hardware, but this could be added through a thickened double-decked shelf. | Provides abundant surfaces for shelving and display, can also be adapted for workstations and equipment stations. |
| 5. Multiple Authors | ![Image] | The design engine is based on the use of law curves to control surface effects and contextual shape. | | | |

Table 1: Design engines from the studio.
component strategies as well as free form surface topologies and law curves driving interactive information-based surface topologies. These modeling strategies and their evaluations comprise the analysis of the success of this research approach. Based on these requirements numerous design engine strategies and emphases were constructed during the project development. We present here several representative design engines; the projects are summarized in Table 1.

Figure 6: Design engine 1 (project materials courtesy of author’s 2006 SCI-Arc student Noriaki Hanaoka).

The first design engine (Figure 6) is based on a driving surface and point instantiation system in which parameterization is based on the pattern of points and the exchange of component types based on simple four point input basis. The pre rationalization of this strategy is to parameterize a system of points based on manipulating simple sketches and then to create possible tile or smart components based on a four point topology. The design engine is built from a smart component (left) and the aggregation into a variable context (middle right). The component is constrained to flat sheet materially and design explored in the abstract (middle left). The image on the right is the externalized physical prototype. The deficiencies of this design iteration include the lack of porosity between the interior and exterior; the cost of flat sheet deformation; and finally the difficulty of integrating hardware for sensing and actuation.

Figure 7: Design engine 2 (project materials courtesy of author’s 2006 SCI-Arc student Chikara Inamura).

The second design engine (Figure 7) is built from a smart component (top) and the aggregation into a variable surface and then full context (bottom). The component itself is tested for its topological adaptability, here exhibiting a wide range of productive design variation from both internal and external parameterizations. In this case the design engine was built of two walls with a gap in between. The affordances of the model include the visual appeal of the overlapping of the differentiated patterning, the ability to vary the depth of the gap and thickness of the walls, enabling the layering of objects and program. The design engine is built from a smart component which is constructed of two parts, front and back (middle left) and the aggregation into a variable surface context (right and bottom). The two part component is constrained to exhibit no undercuts and was conceptually prototyped from unique molds constructed from 3 axis milling and tooling. The image bottom right shows the final prototype and simple use of rods for assembly and structural stability of the two component faces.

Figure 8: Design engine 3 (project materials courtesy of author’s 2006 SCI-Arc student June Yu).

The third design engine (Figure 8) followed a similar strategy of using a driving surface skeleton to manipulate the density of nodal points which serve as both the abstract geometry for instantiation of smart components but as well represent the literal location of the sensors themselves. In this case the design engine was built from two walls with a gap in between. The affordances of the model include the visual appeal of the overlapping of the differentiated patterning, the ability to vary the depth of the gap and thickness of the walls, enabling the layering of objects and program. The design engine is built from a smart component which is constructed of two parts, front and back (middle left) and the aggregation into a variable surface context (right and bottom). The two part component is constrained to exhibit no undercuts and was conceptually prototyped from unique molds constructed from 3 axis milling and tooling. The image bottom right shows the final prototype and simple use of rods for assembly and structural stability of the two component faces.

Figure 9: Design engine 4: three design iterations from one I/O Wall Digital Project Model.
A fourth design engine was built as a pre-rationalization of flat sheet material with automated reconfigurable notching for self-assembly (Figure 9). The design exploration afforded by this system allowed for sculpting in terms of depth of the overall waffling system, spacing, uniform and non-uniform, of the waffle verticals and horizontals and the cutting and shaping in terms of elevation. Adding and subtracting of shelves and stretching into work space areas is also afforded by the modeling strategy. This modeling strategy enabled the team to adjust based on space planning, visual legibility from the interior and exterior view points, and though merging of interaction sensor node density and spacing’s and overlaps, parameters that remain unfixed.

Figure 10: I/O Wall concepts developed by the authors in collaboration with 2007 SCI-Arc students.

A fifth design engine is based on the use of law curves to control surface effects and contextual shape (Figure 10). At issue was the desire to drive the design surfaces based on external parameters (interactive information sets) from the sensor network where different sensor types have different ranges and coverage area shapes. Here the design strategy was to map values for porosity, activity, and sensor density to a series of law curves that reflect perturbation and shape of the surface. The designer-computer interaction is afforded cognitive clarity through the separation of multiple two dimensional graphs that drive a three dimensional surface result. An independent system of node patterns is then projected onto the surface to form the pockets for the technical wiring and shelving to hold and house system components and objects.

The series of images below all focus on the use of the law curve modeling strategy and mapping technique as a means to generate design variants and reduce cognitive load complexi-
ties in the integrating of multiple parameter sets formal and interaction design. The images illustrate the pre rationalized projects as design diagrams and operation recipes; numerous surface variants and surface articulation variants; and finally milled physical prototypes.

2.4.5 Fabrication
For each scheme, issues of project delivery were considered at the inception of design exploration, with some attempt made to encode the limitations or ranges of possible material and fabrication outcomes. Though all the schemes have been prototyped at small scales using 3D rapid prototyping technologies, only one was considered suitable for full-scale fabrication (Design engine 3, Figures 4 and 7). As illustrated in figure 7, fabrication will most likely involve the milling of female molds to be filled with a hard material. An expected advantage to the design and design description methodology is the easy or automated extraction of construction documentation.

One key finding and affordance of the research has been the efficient collapsing of typical design development rationalization techniques to the up stream design conceptualization phases. Another has been the precision and accuracy of the details of the projects that are maintained within every design iteration. For example the flat sheet material project (Design engine 4) has 280 unique notches each of which is automatically reconfigured per shape change but as well through any parameter driven sheet thickness and tolerancing changes. The formalizations of all of the projects in their most advanced state is to confine the constraints of three axis milling and or flat sheet cutting tooling and that of optimization of interactive nodal spacing to accommodate the sensor nodes.

3.0 Discussion and Conclusions
The overall goal of the project was to evaluate the effectiveness of associative parametric modeling in designing structures with integrated computer functionality. Our hope was that a ‘tectonics of sensing’ might also emerge from the projects, suggesting creative strategies for integrating the constraints and functionality of computer inputs and outputs in the overall conception of buildings and building interiors. Despite their limitations, the design engines shown offer substantive circumstantial evidence for the value of parametric design in architectural projects involving integrated computer interfaces.

The following are several distinct strategies that have emerged from the projects.

First, the use of the associative parametric method has provided encouraging results. Once formulated each design engine could be used to generate a large solution space of possible design solutions. Each of these solutions could then be evaluated by the project team in terms of the functional and aesthetic aspects of the interaction design. A second benefit of the parametric approach was ability to easily incorporate constraints imposed by fabrication and by the dimensions and functional characteristics of the sensor network. This resulted in the generation of multiple design schemes, all of which were both buildable and functional in terms of accommodating the embedded technology. Finally, the design engines allowed us to meet our aesthetic desire for an organic, complex surface while adhering to efficient and well-established fabrication methods.

Second, the node-based approach used in the design of the sensor network resulted in an interesting range of node-based design languages. Design engine 3 most clearly expresses the elegance and efficiency of the node-based system. The interior of the node is standardized to accommodate the computer hardware, while the node envelope is allowed to change organically; in the prototype shown no two nodes are identical. Nevertheless, the structure could easily be rationalized to incorporate standard lumber for the horizontal and vertical connecting elements, significantly reducing the cost of construction. In addition, the position of each of the nodes in the x, y and z dimension can easily be manipulated, creating a varying density of nodes that maps the required sensor density in different parts of the space, based on anticipated activity patterns.

Third, the parametric method allows the overall configuration of the wall to be adjusted based on input from the prototype sensor network. The data received from the wireless sensor network can be used to refine the design of the wall as an effective device for sensing the environment. The density of nodes can be increased or decreased as needed, and the distance between the sensors can be adjusted to avoid overlapping ranges or ‘blind spots’. It is nearly impossible to simulate the behavior of sensors in the real world, and the built prototype of the wall will allow us to anticipate problems and refine the final version of the design. Because in each design engine the sensors are located at the intersection of the horizontal and upright shelving elements, these sensor network adjustments will also be visible in the configuration of the wall’s surface.

The primary limitation of the project is the fact that it was not possible to prototype any of the designs at full scale. Nevertheless, the projects do provide a valuable collection of designs that suggest the tectonic implications of embedded computer interfaces.

Bibliography


