DEVELOPMENT OF AN INTEGRATED DESIGN SYSTEM

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Abstract. The School of Design in the Hong Kong Polytechnic University is developing advanced computer-based design systems by integrating Artificial Intelligence and evolutionary computing techniques with CAD/CAAD systems. Applications embrace architectural and environmental design as well as interior, industrial, fashion, graphic, and photographic design. The integration of the design systems developed in these domains provides a good basis for building a virtual design studio in collaboration with leading design research centres and institutions around the world. This virtual design studio is intended as a powerful computational environment for the integration of Asian cultural values with modern interdisciplinary design technologies.

1. Background

Over the last decade the authors have been involved in the development of a number of computer-based systems in the UK for intelligent design support. These systems employed Artificial Intelligence techniques including machine learning and evolutionary computing techniques to support architectural design, engineering design, software design and small molecule design [Frazer 1995 and Tang 1996].

Frazer described an evolutionary model of architecture design in a book entitled "An Evolutionary Architecture" [Frazer, 1995]. In this model, a descriptive language is used to represent an architecture concept in a generic and universal form capable of being expressed in a variety of structures and spatial configurations in response to different environments. The evolutionary model requires an architectural concept to be described in a form of genetic code. This code is then mutated and developed by a computer program running genetic algorithms into a series of models in

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response to a simulated environment. The models are then evaluated in that environment and the code of successful models to iterate the cycle until a particular stage of development is selected for prototyping in the real world. The real world prototype is capable of interactive response to the changing environment on a short time scale. In this approach, knowledge in architectural design is formulated in terms of generic code-script, rules for the development of the code and for mapping the code to a virtual model, the environment for the development of the model and, most importantly, the criteria for selection. In particular, an architectural concept is process-driven; that is, by form-generating rules which consist not only of components, but also of processes [Frazer, 1995].

Other research projects carried out by the authors have adopted a domain independent approach and these projects tackled design problems from an AI perspective by

- establishing a computational model of design at a knowledge level,
- developing an architecture for the realisation of this computational model,
- implementing the architecture using an AI programming language, and
- integrating AI methods into the implemented architecture to support design problem solving activities.

Edinburgh Designer System (EDS) was developed using this approach as part of UK's Alvey large scale demonstrator project 'Design to Product' [Smithers *et al* 1990]. In the EDS project, an exploration-based design model is developed as a knowledge level transformation from an *initial design description* containing only incomplete design requirements, to a *final design description* that satisfies a *final requirement description*. Both the design requirement description and the final design description are evolved in the design exploration process.

The EDS was developed using a generic knowledge based design support system architecture. This knowledge based architecture integrates a number of AI techniques to support design activities in terms of constructing design models from building blocks of past design, exploring design problems by making modifications to the design model, and generating alternative design solutions by exploring the contexts of the design model [Smithers *et al* 1990 and Tang 1996].

The EDS architecture consists of a declarative design knowledge base, an assumption-based truth maintenance system for maintaining multiple contexts of design, a design documentation system recording the history of a design project, a blackboard control system controlling a number of *design knowledge sources*. The design knowledge sources act as inference engines for propagation and satisfaction of functional, spatial, geometric and relational constraints associated with a design model.

The EDS was firstly developed in UK's Alvey large scale demonstrator project 'Design to Product' as part of a mechanical engineering design system. Its exploration-based design model and knowledge based architecture were further developed in two separate domains for validation. One project, the EDS2 project, addressed the problem of intelligent control and consistency maintenance in large scale knowledge-based design systems [Smithers *et al* 1993]. The other project, the Castlemaine project, tackled the problem of applying EDS design model and architecture to small molecule drug design and software design. The Castlemaine project involved UK's major knowledge based software system developer, Logica Cambridge Ltd., and domain experts in British Bio-Technology Ltd. in Oxford. The Castlemaine system supported the synthesis of new drugs from existing small molecules [Smithers *et al* 1993].

The methodologies and computational components in EDS, EDS2 and Castlemaine system were further formalised as an AI-based design support system architecture [Tang 1995 and 1996]. In this generic architecture, a blackboard control system is integrated with an Assumption-based Truth Maintenance System (ATMS) to provide a framework for the development and integration of knowledge based design applications. This architecture also has an inductive learning system for learning design concepts from past or existing design examples [Tang 1996]. This AI-based architecture was subsequently used by one of the authors at the Engineering Design Centre in Cambridge University in the development of an Integrated Functional Modelling System [Chakrabarti *et al* 1996 and Tang *et al* 1997].

One of the main lessons learned from the above research projects is the division of effort between a *general purpose* approach and a *domain specific* approach to computer-based design. While the development of computational design theory and methodology can in general improve our understanding of the design process, AI in design research must commit more to a data intensive approach and involve designers across different domain more in research projects. Designers always have a role to play in any advanced design system. They also have a central role to play in developing such design systems.

However, most of above described approaches and systems have adopted design models that are unable to present information and knowledge in the crucial early stages of design process, which is conceptual design. Furthermore all these systems have been developed largely in a European context and the software systems developed in these projects have been implemented on software and hardware platforms that are not necessarily suitable for Hong Kong and China's industry.

An interdisciplinary approach is needed in order to build a framework within which those techniques developed by the authors in the UK can be validated, integrated and enhanced to suit Hong Kong's needs. In order to do so, the following issues must be addressed:

- representation and systematization of design knowledge and information,
- intelligent control of design process,
- consistent maintenance of design knowledge,
- design history documentation,
- 3D visualisation and explanation of product and process,

- evolution of design requirements as well as design solutions,
- learning in design, and
- cultural and environmental issues.

2 An Integrated Design Support System

The School of Design in the Hong Kong Polytechnic University is promoting research to combine useful ideas and computational techniques from architectural design and engineering design for the development of a generalised computational environment for interdisciplinary design collaboration. This is based on the belief that the techniques for design concept generation, evolution of design requirements as well as solutions, constraint management, and 3D or Virtual Reality visualization are necessary for both domains. Furthermore both architectural and engineering design researches have similar needs for the development of

- modelling techniques currently unavailable in commercial CAD/CAAD systems;
- rapid conceptual design and constraint-based techniques, leading to a better evaluation of competing alternative design solutions; and
- evolutionary techniques for design optimisation.

It is argued in this paper that architectural design applications can benefit from the design techniques derived from engineering design. This argument is supported by our experiment on the integration of evolutionary computing techniques developed in architectural design with AI-based engineering design techniques developed in Edinburgh and Cambridge [Frazer, 1995, Ball *et al* 1992, Tang 1995, Chakrabarti *et al* 1996 and Tang *et al* 1997]. This integration is currently being carried out in a project called ‘adding generative capability, database intelligence and virtual prototyping facilities to computer-aided design systems for design evolution and optimization’ [Frazer 1997].

In our integrated approach to intelligent design support, the building blocks of design or examples of past or existing design are represented as frames in advance in a *design knowledge base*. Several general purposed design knowledge sources (or support systems) are developed to support the following design activities:

- synthesis at an abstractive level of conceptual design solutions from building blocks of design and initial design requirements using generative and inductive learning techniques,
- transferring conceptual design solutions into detailed design models containing spatial, geometric and structural knowledge,

- manipulation and partition of detailed design models into smaller design problem spaces containing suitably constrained design variables and constraints,
- searching for solutions in the partitioned design problem spaces using evolutionary computing techniques,
- exploration and maintenance of alternative design solutions when considering different design issues, and
- documentation and explanation of design results and design history.

The design knowledge base and design knowledge sources form the core of an integrated design support system that is being developed in the School of Design in the Hong Kong Polytechnic University. A self-contained software system kernel known as the Assumption-based Truth Maintained Blackboard System is used to control the design knowledge sources and integrates external CAD and CAAD systems [Smithers *et al* 1990, 1993 and Tang 1996]. The integrated design support system is intended to support the development of knowledge-based design applications in both architectural and engineering domains.

The design knowledge base contains design objects, relations, constraints in terms of intended function and interfaces as well as detailed information in terms of materials and geometry etc. The design knowledge base is developed in advance by a knowledge engineer or by the designers themselves.

The design objects in the design knowledge base can be selected and synthesised using a generative program based on a functional synthesis system described in [Chakrabarti *et al* 1996] to generate conceptual design solutions. At an abstract level, a conceptual design solution identifies the basic components and their topological arrangement to the satisfaction of a stated initial design requirement. At the early stage of the design process, many alternative conceptual design solutions must be explored, analysed, evaluated, and selected before putting a concrete design concept forward for further investigation. A design concept learning system described in [Tang 1995] is used to cluster and structure alternative conceptual design solutions using unsupervised inductive learning techniques. In this way, past design examples or basic elements of design in engineering or architectural domain are used to derive a design concept tree. From this design concept tree abstractive conceptual design solutions satisfying an initial design requirement can be browsed by the designers. The use of generative and machine learning techniques makes sure that a large number of abstractive design concepts are explored before detailed geometric embodiment or structure configuration are carried out.

Once a conceptual design solution has been selected from the design concept tree by a designer, it is transformed into a detailed design model using the knowledge stored in advance in the design knowledge base. A detailed design model contains design variables and constraints describing the structural and geometric feature of the design. For example, in mechanical engineering design, a detailed design model has variables and constraints representing assembly, embodiment and kinematic information of a product whilst in architectural design, a detailed design model has variables and constraints representing the structure, style, materials and environment of an architecture.

A detailed design model is computationally represented as a network of design variables and constraints so that it can be manipulated by members of a design team using *constraint-based techniques* [Smithers *et al* 1990]. The network of design variables and constraints of a detailed design model can be partitioned into smaller sets. AI-based searching methods such as simulated annealing and genetic algorithms can then be used to find out a set of design variable values that best satisfies the constraints. This partition can be done based on

- mathematical relations of the design variables,
- assembly of the product or configuration of the architecture, or
- heuristics introduced by designers.

A partition of the constraint network identifies a small region of the design space. This small design space can then be meaningfully explored using evolutionary computing techniques such as genetic algorithms used in the evolutionary model of architecture. The evolutionary computing techniques described in [Frazer, 1995] addresses an architectural design problem as a *goal-directed search problem*. This evolutionary approach is also valid in engineering design applications [Thornton 1993]. In both applications, the goal is to minimise the number of constraints that are violated.

The process of exploring a detailed design model involves symbolic computation in terms of constraint propagation and satisfaction. This exploration process is also common to both architectural and engineering domains. However, whilst the evolutionary computing approach described in [Frazer, 1995] relies more on automatic formation and evolution of architectural concepts, the synthetic and heuristic approach described in [Chakrabarti *et al* 1996 and Tang *et al* 1997] emphasises the use of symbolic computation and heuristic-based evaluation and selection of a potentially large number of solutions before any automatic searching methods are used. The latter is particularly important in engineering design where the search space for a design solution needs to be confined to small regions before genetic algorithms can be usefully employed [Thornton 1993]. To combine these two approaches to provide support to both architectural design and engineering design, a constraint management system is being developed [Tang 1997].

Components of this integrated design support system including a graphical explanation system and a design documentation system are integrated with commercial CAD and CAAD systems. Applications in both architectural and engineering design are also being developed to validate the integrated system in several research projects [Frazer 1996 and 1997].

3 Towards a Virtual Design Studio

The integration of computational techniques developed in architectural and engineering domain provides a good basis for the development of a Virtual Design Studio (VDS) in the School of Design in the Hong Kong Polytechnic University. The VDS is intended to support the designers of different fields in Hong Kong through *global design collaboration* by

- providing sophisticated computer-based design techniques and resources for the design industry in Hong Kong to evaluate, select and use advanced CAD and CAAD systems for design and management,
- providing integrated global design services using tele-conferencing and web-based design collaboration techniques for the designers in Hong Kong to work with global partners, service providers and potential clients.
- providing facilities and guidance for the design and manufacturing of hi-tech and high-quality products through training courses and seminars that can be delivered on a global basis.
- integrating academic research, education and industrial applications in design technology using the best available AI techniques and Internet techniques.

Two particular focuses of the VDS are: to address interdisciplinary design collaboration by providing general purposed as well as special purposed computational support to architectural, industrial, engineering, graphic, photographic, interior and fashion design; to use Virtual Reality visualisation, teleconferencing facilities and web-based design collaboration system to encourage global design collaboration.

As illustrated in Figure 1, specific knowledge modules and applications are developed in different domains of design. However, management of knowledge base, intelligent control of design process, and general purposed computational support are provided by a super computer for design applications all domains. The Virtual Design Space is a dynamic design workplace shared by the design applications in all domains. For example, it can be used for virtual product design and exhibition, virtual fashion show, virtual photo workshop or virtual interior design workshop etc. The video-conferencing facilities and a web-based design management system are integrated into the Virtual Design Space for international on-line or web-based design collaboration.

The tools to be integrated into the VDS are classified into four categories: generative and evolutionary computational tools, AI-based symbolic computational and constraint-based tools including machine learning tools; commercial CAD/CAAD tools, Internet, and ISDN-based tools; and domain specific tools. These tools are controlled by an intelligent control system running on a SG Onyx2 computer and a cluster of Unix workstations.

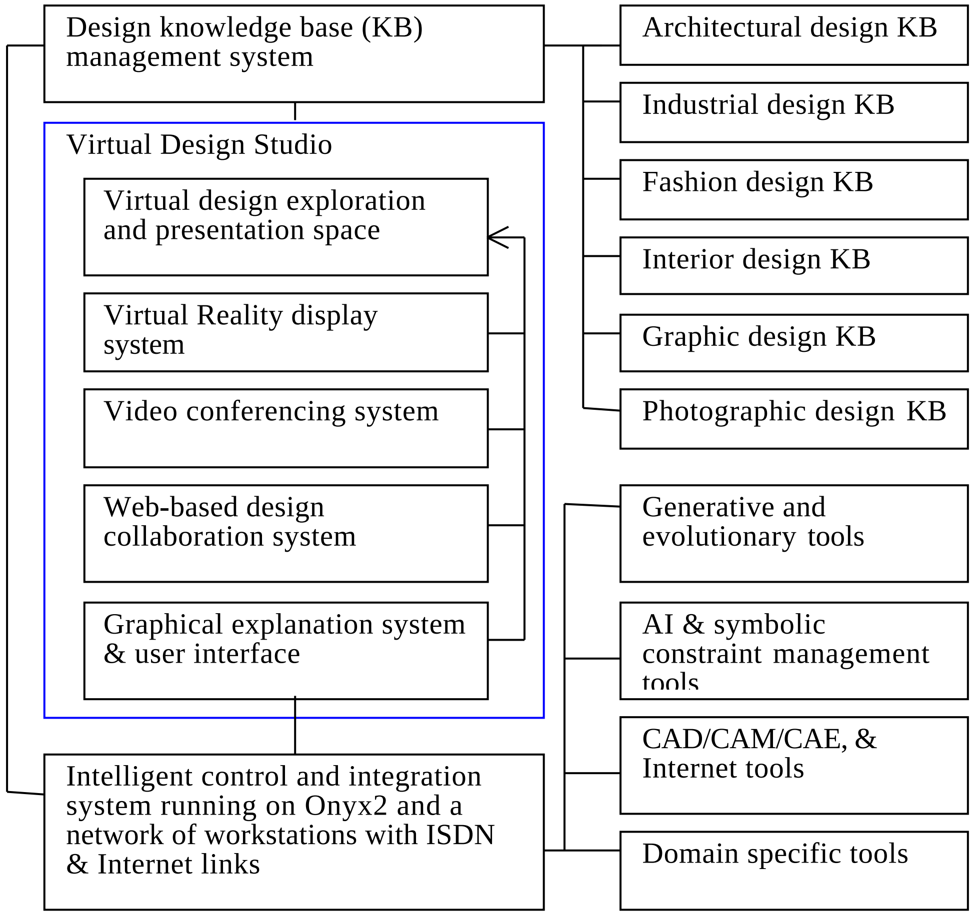

Figure 1: **Virtual Design Studio**

The VDS is expected to achieve the following objectives: a significant reduction in design time for small high-tech companies in Hong Kong as a result of using the integrated design services offered by the VDS; a substantial increase in opportunities to identify new products or new clients as a result of quick and effective access to global design network for market intelligence and client requirements for Hong Kong's managers and designers in major design profession; a reduction in travelling and expenses for design professionals in Hong Kong in their business collaboration activities, a significant cut in professional training costs for the design professionals who have otherwise to go to training courses offered by foreign companies and institutions; the majority of design professionals in Hong Kong will be able to utilise the facilities offered by the VDS for their design research; and a number of design-led business in Hong Kong will be able to use the techniques of VDS for the experiment to control and manage their factories in China.

A key issue regarding the VDS is that its Virtual Reality visualisation system must be seen as an integral part of an AI-based design support environment in order to provide *integrated design services* to the designers in Hong Kong and others parts of China. Without AI-based support to interdisciplinary design activities, the potential of VR visualisation techniques cannot be effectively utilised.

Another issue in the VDS project is about how to incorporate Asian cultural values in the studio. While the VDS is being developed as a platform for multi-disciplinary and international design collaboration, its main focus is on the application of computer-based design technology in an Asian especially Chinese context. The services and techniques offered by the VDS must support the designers in China to create products or architecture that have a strong Asian cultural identity. The VDS will be used to promote awareness of culture related design issues such as user and environmentally friendly design and use of traditional materials.

5 Conclusions

Our research on the development of an integrated design support system and a Virtual Design Studio contributes to architectural design as well other domains by integrating an evolutionary model in architectural design with AI-based design techniques developed in engineering design. This integration provides a framework for developing knowledge based design applications in both domains as well as other domains.

In conclusion, an integrated application of AI techniques for computer-based design has been presented. Several issues have been identified in order to validate these integrated AI techniques in the development of a Virtual Design Studio for global design collaboration and management. Our Virtual Design Studio is to provide general support for different kinds of design activities in different domains. The development of the VDS has just started and it will provide a unique environment for research and development of computer-based design technology in Asia in general and in China in particular.

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