A Knowledge-Based CAAD system with Qualitative Spatial Reasoning Capability

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Design and creativity go hand in hand. The ability to be creative in design can be enhanced when humans and computers, which both work as information processing systems cooperate in a complementary, integrated manner. Computational systems should play the most essential role in enhancing creativity within human-machine design systems in the future. In this context, we present the concept and architecture of a new integrated CAAD System, AutoNEO, that will support the achievement of creative results. We will focus on the qualitative spatial reasoning capability of AutoNEO, and provide an example of layout design as a case of qualitative spatial reasoning.

Keywords: knowledge-based CAAD system, qualitative spatial reasoning, design creativity.

1 Introduction

The goal of CAAD system is on the invention of an intelligent and integrated system which will support architectural creativity and promote the free exchange of information among the various professionals who participate in the process of architectural design. This future CAAD system should enhance architects' spatial reasoning at the stage of conceptual design in order to maximize creative thinking.

The existing CAAD system has a poor connection between its drafting system and knowledge based system. As yet, there is no methodology for qualitative spatial reasoning for creative design. In the past, the study of building data integration has been conducted on the basis of object oriented modeling and data base techniques for the invention of an integrated CAAD system. Although the research on the process of integration is being conducted, it does not take into consideration the creativity of architectural design.

Creative reasoning happens mainly through the interaction of geometric and topological information with high-level symbolic spatial meaning at the conceptual design phase. This paper, therefore, will propose the concept and architecture of a new integrated CAAD system, AutoNEO, and explain its characteristics. In addition, the study will present an example of the technology of qualitative spatial reasoning which support creative architectural design.

The knowledge-based system for creative architectural design ought to connect graphical data with qualitative spatial knowledge. The common sense reasoning method of artificial intelligence is utilized to support geometric modeling and spatial reasoning. AutoNEO is a knowledge-based system which can support the abstraction of higher level information and share the data model with AutoCAD. Moreover, AutoNEO can be operated with the existing ADS of AutoCAD which comes from a Windows-based system.

Qualitative spatial reasoning in AutoNEO consists of three parts : interpreting geometric and spatial information of design elements from graphic primitives, translating this information into high-level qualitative architectural meaning, and thinking logically with the high-level meaning.

2 *Creative design* with qualitative spatial reasoning

2.1 Creativity in architectural design

Designing is an information processing behavior and creative solutions occur when a new formulation of the design task is generated or when a solution is discovered in a region never examined before. According to R.A.Finks Gene lore model of creative cognition, creative architectural design may occur in the process of generation, exploration (interpretation), and modification (refinement) of building forms [1].

We analyzed the architectural design process using the Protocol Analysis method [2]. Twelve designers participated in this research. As a result of this analysis, we found out that creative design decisions were made in each stage of the design process.

In the problem definition stage, the designer develops the design concept and identifies the design objectives and constraints using his or her experience as well as the knowledge and information given through the design brief. The decision made here plays a great role in directing the direction of design for creative solutions.

The designer also takes into account the size, shape, location and material of design elements in a given drawing and identifies the relationships among the design elements. In addition, he or she distinguishes the design variables that become the object of designing from fixed variables and makes a decision about the possibility of changing fixed variables into design variables. This is the design strategy that limits design problem space and focuses on important design variables.

In the stage of design development, the designer produces various design alternatives rather than simply focusing on one possibility. During the process, of course, some of the more satisfying alternatives are fully developed through evaluation. Still, the challenge remains to find a new alternative even if the existing one is satisfactory. Thus, the more alternatives that the designer produces, the greater the possibility for a more creative design solution.

The designer produces a new alternative, changing fixed variables into design variables when none of the alternatives, that are produced up to now, is satisfactory. The designer quickly builds a new and satisfactory alternative utilizing the accumulated design information. In this case, a fixed variable, that is related to the most critical design constraint or to the problem that has not been solved in the former stage, or has the lowest degree of fixation, is preferentially changed into a design variable.

In the stage of design evaluation and selection, the designer introduces new constraints. These constraints were not considered in the process of design development but are now used in the evaluation and selection of satisfactory alternatives. Here, the alternative with the richest meaning is selected.

In the stage of design refinement, the designer selects the appropriate size for the design elements, elaborates on the shape of elements, adds details that have not been considered, and completes the creative design solution.

The creativity of architectural design depends on finding the possibility of new problem solving by introducing new design variables or constraints. In other words, the distinction between design variables and fixed variables must be re-considered during the design. Also, the accumulated creative decisions from each stage result in a creative design solution at the end.

2.2 Qualitative spatial reasoning in creative design

Creative decision in the architectural design process is mainly a result of spatial information processing. The spatial information which is processed in architectural design consists of geometric information, which is related to the size, shape of design elements, and relational information, which stems from spatial relations among design elements.

What appears to be most important in the creative design process is to be able to transform verbal concepts to spatial (imaginable) information and back again so as to gain multiple perspectives on the design task at hand. Specifically, there are some problems that can be solved by imagining the spatial relationships among the design elements, and 'seeing how the relationships change over time.

In other words, qualitative spatial reasoning in architectural design 'sees" graphic elements in a drawing or mental image, draws geometric and spatial information for design objects, and understands high-level architectural meaning with the use of drawn information. At the same time, logical thinking such as deduction or induction is processed with the abstract meaning. In addition, qualitative spatial reasoning includes spatial visualization that interprets architectural meaning or intention(such as design concept, design objectives, design constraints), into the physical properties of design elements and spatial relationships among them. Thus, the architectural meaning is inferred from the spatial relations in visual image. In addition, the change of spatial relationship is directly induced from the change of design intention.

In this spatial reasoning process, creative solutions can be made by creating new descriptions of the relationship among the design elements (i.e., by joining the elements in novel ways, specifying a new frame of reference, introducing new design elements or design constraints, and so on).

2.3 A CAAD system for enhancing creativity

The creative design occurs when a designer is provided with the opportunity to explore an expanded problem formulation or more of a given solution space. We view humans and computers as information processing systems. A CAAD system for enhancing creativity will have to recognize the limitations of human designers and incorporate a symbiosis between the machine and the human designer. A CAAD system should be able to identify what human designers need in the creative design process and help them in order to cooperate interactively with the designers. As mentioned before, creative architectural design comes from the designer's qualitative spatial reasoning through mental imagery.

Thus, a CAAD system for enhancing creativity should meet the following conditions.

(1) It should be able to extract high-level semantic information from the visualgraphic data.

(2) It should be able to translate high-level design intention/ meaning into geometric properties of design elements and spatial relations among them.

(3) It should be able to apply a design strategy to limit design problem space by distinguishing design variables from fixed variables.

(4) It should be able to produce all possible design alternatives.

(5) It should be able to produce a new alternative by changing fixed variables into design variables.

(6) A designer should be able to evaluate any alternative produced by the system and to import new constraints when evaluating design alternatives.

(7) A designer should be able to input all acquired knowledge (constraints, objectives, new design variables, etc.) during the design into the computer.

Thus, the computer should be able to integrate the intention of the designer who is using the computer. This is critical to the symbiosis of human designer and the computer. In the future, a designer will simply be able to tell a computer what he or she thinks during the design process, and the computer will be able to accept and accumulate it using a speech recognition system. All these processes will critically influence creative design.

The CAAD system for enhancing design creativity should be intelligent in its nature. The intelligent CAAD system is engaged in upgrading the quality of the solution through enhancing productivity and creativity in all fields and stages during the design process.

3 A CAAD system using knowledge-based techniques

3.1 AutoNEO System

For the Knowledge-Based System to perform cognitive processes during the design process, sharing data structures with the CAD tool is necessary. Furthermore, communication with the CAD tool should be possible. In case of the AutoCAD that is being used by many designers, it is possible to add this function through ADS, AR)(. Many solutions that have used this open structure of AutoCAD have been developed by third vendors. AutoNEO is a system that integrates kernel engines of the NEO(Name Equals Object) system, which was developed to represent and process knowledge and real world problems with the application module of AutoCAD.

AutoNEO has multi-agent processing architecture in order to seamlessly integrate many functions and strategies related with architectural design. Each agent is based on objective modeling and has its own goal as well as the knowledge and resource to achieve its goal. It has the capability to work with other agents. The information modeling of this system is based on the object-oriented method, a type of prototype delegation. Since the object-modeling based on prototype is similar to designer's cognitive processing and therefore more flexible than modeling based on class, it is suitable to the real world modeling to support creativity. In this system, delegation is the method by which resources and codes are shared among agents. The inference mechanism supports bi-directional reasoning of backward/forward chaining. Moreover, dynamic conflict resolution strategy can be applied through meta-reasoning.

3.2 The Architecture of AutoNEO System

(1) Integration of AutoCAD and NEO kernel

AutoNEO is a combined system of AutoCAD and NEO kernel that is an example of knowledge representation and inference engine. NEO kernel is a knowledge inference and computation processing system that integrates knowledge inferencing, object modeling, object computation, and functional computation, in order to make representation and calculations. It is designed and implemented as a kernel type to perform intellectually when ported into many different system.

NEO kernel consists of three engines that support three different paradigms, consisting of knowledge, object, and function. Each of these paradigms has been used and developed in the problem-solving field. Many tools and languages have been developed for each. There also have been many experiments combining two or more paradigms.

These experiments so far, however, have been tried at the tool or language level. Therefore, examples possessing integrated paradigms that are actually used for ordinary sytems are rare. This is because syntax is complicated and difficult to use awing to dissonance among concepts.

The structure of AutoNEO is shown in Figure 1.

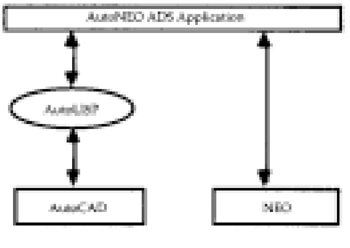

Figure 1. The architecture of AutoNEO

(2) The general problem description and solving tool NEO

The mixed use of object oriented techniques, Knowledge-Based System, and script language is inevitable. Object oriented techniques and Knowledge-Based Systems are essentially used in structuring systems which consider productivity and creativity. Script language is needed when structuring many different systems into one integrated structure. But the research on the method that enables them to be modeled into a coherent concept and to describe them in simple syntax is rare. NEO is the system that has been studied in order to develop these problem descriptions and problem-solving methods that are needed in many fields like CAD. NEO can integrate the tools and languages such as expert system development tool, object-oriented models and languages, and functional computation language within the coherent concept. The knowledge or problems represented by NEO are modeled into objects and represented by a list. A typical NEO object can be one of the following: production rule, objects in Smalltalk and Actor, or functions in LISP. It can also be a composite of all the above.

The following is a grammar example of NEO object.

```
(R1 if (?x is-a polygon)(?x boundary closed)(?x internal hatched))
(R1 then (?x is-a wall))
(R1 priority 100)
(R1 comment ì R1 is a wall objectI)
(R1 (:zoom ratio ?r)(
// this is a message pattern of R1 object
// it performs zoom in/ out the wall ?x with ratio ?r))
(R1 (:move :right ?rx)(
// this is another message pattern of R1 object))
```

NEOs rule inference engine basically performs backward inferencing and conflict resolution by priority. The computation of NEO System can be started by setting a goal and sending a message. The process continues until the goal is established or until there is no longer an effective message in the system.

The structure of NEO is shown in figure 2.

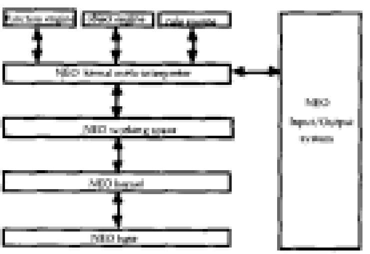

Figure 2. The architecture of NEO

4 Qualitative spatial reasoning system

4.1 The role of qualitative spatial reasoning in AutoNEO

AutoNEO System is a Knowledge-Based System Developing Environment that enables integration with AutoCAD. It is hard to achieve the goal through simple reading and writing for data exchange in the developing environment. Spatial information of design elements, which designers think with, are very abstract. Therefore, the developing environment must have the ability to relate simple graphical data with the designers high level knowledge in order for AutoCADs simple graphic primitives to be used in the architectural design thinking.

Qualitative Spatial Reasoning System has an inference mechanism that is made to integrate design objects, spatial relationship and spatial representation processed b designers, with computers simple graphic primitives. Knowledge-Based System with spatial reasoning (a kind of commonsense reasoning) capability can process spatial information of design objects.

Qualitative Spatial Reasoning System in AutoNEO provides basic spatial inference ability as a part of AutoNEO and performs the role that makes it easy to develop intelligent CAD System in architectural design field.

4.2 The operation of qualitative spatial reasoning system

When a drawing that is made with AutoCAD is inputted to AutoNEO, Qualitative Spatial Reasoning System in AutoNEO constructs basic geometric elements such as point, line, plane from simple graphic data with the use of geometric knowledge, then identifies the spatial relationship among geometric elements with topological knowledge[3]. After that, the meaning of the spatial relationship is constructed using architectural knowledge. However, the meaning of architectural elements through the above process cant become enough abstract for architectural design thinking. This is because not only physical and functional architectural elements but also cognitive spatial meaning must be considered for architectural design thinking.

Thus, cognitive architectural space that is made through physical architectural elements should be the object of inference. This abstract knowledge of architectural space is somewhat subjective, but the universality of information for communication among design experts may be allowed. Qualitative spatial reasoning in AutoNEO becomes integrated with the designers abstract knowledge through the transformation of a simple graphic data into abstract spatial meaning. The Knowledge-Based Design System makes it possible to represent the attributes of various design elements and spatial relationship through qualitative spatial reasoning.

4.3 The principle of the system

The most important element in spatial reasoning is qualitative shape description. Quantitative spatial reasoning not only requires much calculation time but is also much different from human spatial reasoning. However, the use of pure qualitative representation without using numbers in computers spatial inference is questionable. Therefore, qualitative spatial reasoning uses mixed symbolic/quantitative representation (MD:Metric Diagram) and purely symbolic description(PV:Place Vocabulary) of shape and space[4]. Place refers to spatial elements, such as point, line, plane, and qualitative spatial reasoning about space provides vocabulary describing the relation of place symbolically.

Symbolic predicates related to spatial inference of this system are processed by quantitative computation in MD/PV model. The Metric Diagram can be used as an oracle for spatial questions. This study is about applying qualitative spatial reasoning used in motion reasoning of qualitative physics and will be expected to be applicable to dynamic spatial interpretation in architectural design. Furthermore, the MD/PV model may be a good representation for spatial reasoning. There has been a strong suggestion and evidence that the computations involved in vision and imagery are tightly linked, even to the extent of being shared hardware. Therefore, the MD/PV model is expected to become a tool for realization of various theories on designers visual thinking.

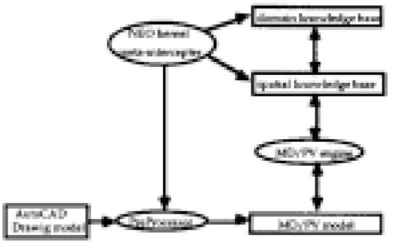

Figure 3. Qualitative Spatial Reasoning System in AutoNEO

Graphic objects in a AutoCAD drawing that are inputted to use the MD/PV model in this system, need a pre-processing procedure that changes them into symbolic representation of boundaries. It is possible for a MD/PV model designed for specified drawing to realize various spatial predicates, but it is not always possible to do all spatial inference in that MD/PV model not only processes spatial properties of object but constructs a basis of representation for abstract spatial information. Thus, spatial predicates of MD/PV model are primitive in this system and they are used in the inference of architectural spatial reasoning.

Though there are many strategies for creative design in architecture such as prototype modification, generation of analogy, modification operator, the design elements which they deal with, have spatial characteristics. Spatial characteristics are not limited within the physical attributes such as size, location, shape of elements, but are abstracted into high-level meaning through the relation among elements in space. The effective abstraction of the spatial meaning is essential, no matter which creative strategy is used. The creative designer understands and analyzes problems and accumulates experience through spatial abstraction. Therefore, Knowledge-based Architectural Design Developing System with qualitative spatial reasoning capability can be an effective tool for various creative design strategies with use of representation and inference of abstracted information.

5 Running example: layout design

Layout design is a work to decide the location and direction of design elements considering spatial relations and to decide the size, material, shape of design elements. Layout design is a generic phase or process of architectural design. Layout design is inherently difficult because of the large number of location and orientation combinations available for placing any simply design object. Furthermore, there are multiple interdependencies among the design objects imposed by their shapes, sizes, and the spatial relationships required to meet multiple performance requirements. For these reasons there is no direct method that is guaranteed to produce immediate satisfactory solutions.

Layout design is a suitable design task for the running example of the AutoNEO System. The following description of the AutoNEO System does not emphasize technical details or the current realization of all of its components. Rather the intention is to provide a capability of the system. The primary goal for AutoNEO has been to build a partiallyautomated system combined with a human designers creativity. Design task of the running example is layout design of a bathroom[5].

A protocol analysis study of a bathroom design process, conducted in this project, has reveled that the knowledge utilized by designers can be modded as several distinct categories. We use the underlying model developed by Chinowsky[6] to capture the typical knowledge used by designers during the bathroom design process. This model represents a characterization of the layout generation knowledge and the layout information used by designers.

The layout information is classified into topological attributes, design attributes, and spatial reasoning concepts.

Topological Attributes - The layout information represented in this category provides the topological constraints and guidelines for the design of individual objects such as toilet, tub, washbowl, or bathroom. These attributes include typical square footage requirements, typical dimensions, typical length-width ratio, and other information related to the physical shape or dimensions of a design object.

Design Attributes - An organization of the layout information has been developed based on the attributes related to the design of the bathroom, such as daylighting and spaciousness of the bathroom. This organization permits the designer to retrieve information as it relates to an individual design object. This information may then be used as the constraints or guidelines for the design object in a particular design process.

Spatial Reasoning Concepts - A designer utilizes information related to typical spatial reasoning concepts such as spatial relation concepts (ex. privacy or publicity, using partition or not). These concepts provide the designer with a basis from which to develop a layout.

The framework for layout generation knowledge consists of designer expertise, design attribute heuristics, spatial reasoning heuristics, and knowledge selection heuristics.

Design Attribute Heuristics - This category comprises the layout generation knowledge necessary to utilize general design attribute information such as daylighting levels and typical adjacencies among design objects.

Spatial Reasoning Heuristics - The generation of spatial placement options requires knowledge of the spatial reasoning concept being employed by the designer. For example, the generation of placement options for privacy will vary from those generated for publicity. Thus, specific knowledge is included in this category to facilitate the generation of possible placement options according to the spatial reasoning concept under consideration.

Knowledge Selection Heuristics - The knowledge selection heuristics represent the knowledge which a designer utilizes to determine when to alternate between various phases of the design process and when to use different sources of layout knowledge.

Designer Expertise - An important aspect which a designer brings to a problem is his or her expertise developed over a period of time addressing the bathroom design. Through this experience, the designer develops intuition concerning the proper focus for an evolving layout. A segment of this knowledge which addresses the typical selection of

spatial reasoning concepts and the overall evaluation of an evolving layout is incorporated in this category.

The representation of layout information and knowledge within the model categories is accomplished in the AutoNEO system through topological attributes hierarchies and rule sets. These representation paradigms have been selected based on the necessity to relate layout information and knowledge with individual design objects. For example, daylighting information in the design attributes category must be represented in a manner which permits the information to be related with the design object.

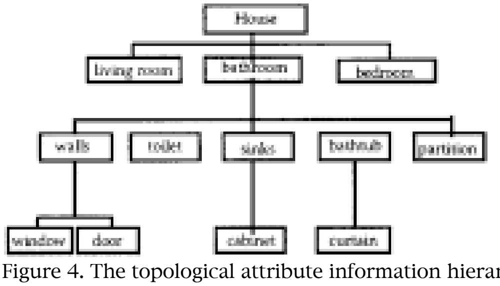

Figure 4. The topological attribute information hierarchy for the bathroom design.

The topological attributes hierarchy represents the fundamental design object organization in the knowledge model. (figure 4)

The rule set representations focus on the heuristic knowledge associated with the layout generation knowledge categories. The rule sets may be viewed as small expert systems, each of which focus on a particular aspect of layout generation.

This layout design of a bathroom goes through 5 stages of the interaction of the AutoNEO System with the designer.

5.1 Information inputting stage for design

(1) AutoNEO System: asks for graphic information in which present situation or design boundary condition is expressed.

(2) Designer: inputs draft in which present situation or design boundary condition are expressed.

(3) AutoNEO System: (i) identifies the size, location, shape, and material quality of elements(wall, door, window, sink, bathtub, toilet, partition, etc.) and (ii) decides upon the design variables and fixed variables(deciding priority among fixed variables' degree to change into design variables).

5. 2 Design development stage

(1) AutoNEO System: draws all the relations that satisfy design objectives or design constraints and makes design alternatives. For example, the system decides the location and direction of the toilet considering the relationship with the door by C1(the

privacy when using the toilet), decides the location and direction of bathtub considering toilet location and C2(the privacy when using the bathtub), and decides the location an direction of sink considering C3(the spaciousness of the bathroom), common senses and all of the above fixed elements. Also, it can decide the location and direction of the toilet, with the partition considering C1, then decides the location and direction of the bathtub and partition with the use of C2 and toilet location.

(2) Designer: can develop one alternative that he or she likes in the generation process of AutoNEO System. He or she can then evaluate the alternative. AutoNEO System entrusts the evaluation of the design solution to the designers. The designers can then develop one alternative more in the process.

5.3 Design decision stage

Changing fixed variable to design variable

(1) AutoNEO System: creates all design alternatives after changing the fixed variables that can be easily altered to design variables. For example, the system (1) makes an alternative after changing the doors location (a fixed design variable) then, (ii) makes one with a different window size (another fixed variable). However, the location of door and the size and location of wall cannot be changed. The priority of order to be changed among fixed variables are: (i) Those which are related to the most critical design constraint or objective. ii) Those which have a low intensity of fixation. (iii) Those which are related to problem-solving in previous stage.

(2) Designer : can change the priority of order of fixed variables and evaluate design alternatives(cross-checking with former idea).

Importing new design variables

(1) AutoNEO System: imports new variables and develops new design constraints. If a dresser is designated as a new variable, a new constraint is created which locates the dresser near the sink, making it closest to the door. The range and order of new design variables are decided beforehand in the system.

(2) Designer: can add new design variables randomly or according to the request of the system.

5.4 Evaluation and selecting final alternative

(1) AutoNEO System : verifies (i) all alternatives, (ii) alternatives selected by the designer, or iii) alternatives coming from the last stage with use of constraints that are made during designing and new constraints, and decides the final alternative.

(2) Designer: can evaluate and select the final design for himself /herself. In this stage, the whole space of the final alternative can be evaluated in a three dimensional graphic model.

[Constraints are most important knowledge that is acquired and accumulated during the design process. It is important to keep in mind that new constraints for evaluation are qualitative.]

5.5 Refining final design

(1) AutoNEO: refines each element of justified alternative, for example, rounding sink edges, changing the shape of bathtub, making stairs for bathtub, changing size, etc. Details, such as curtain, cupboard, radiator, plant pot, towel hanger, etc. can be added. It is possible to add details or refine each element using two or three dimensional graphics. The size, direction, shape, and location of added elements are decided in relation with existing design elements. The range of refinement should be decided beforehand.

(2) Designer: can design details for him/herself on the screen. Also, the user should be able to evaluate the result of adding details and refining elements. After all, the user finishes the design process.

6 Conclusions

In this paper we have described an approach to the computational environments that can be used to support creativity in design. We have proposed conjectures regarding creativity within an information processing theory of design. These conjectures predicate the occurrence of creative design when a designer is aided by the CAAD system with the capability of qualitative spatial reasoning. With this system, a designer is provided with the capability to explore an expanded problem space or more of a given solution space for a task. We have characterized the realization of design environments to enhance creativity. By describing AutoNEO, an architectural design system, we have illustrated how the condition of our conjecture could be supported in Knowledge-Based CAAD environment. Although it appears that our implementation and experiments have not yet addressed the development of a creative design, we have addressed the role of computers in supporting this goal.

7 Endnotes

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