A GRAMMATICAL APPROACH TO AUTONOMOUS DESIGN IN 3D VIRTUAL WORLDS USING GENERATIVE DESIGN AGENTS

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ABSTRACT: 3D virtual worlds are networked environments designed using the place metaphor. 3D virtual worlds as Computer-aided Design (CAD) tools have shown promising potentials in areas such as design simulation, distant team works as well as interdisciplinary design collaboration. Recent developments in collaborative 3D virtual worlds focus on interactivity, flexibility and adaptability. Rather than creating virtual environments in which the 3D objects have intelligent behaviors, we take a different approach to develop an agent model that is associated with an individual designer in a 3D virtual world as a personal design agent. This paper presents Generative Design Agents (GDA), a kind of rational agents that dynamically and automatically generate, simulate and modify designs in 3D virtual worlds. The core of a GDA's design component is a generative design grammar that is able to generate designs capturing a specific style in 3D virtual worlds. 3D virtual worlds augmented with GDAs provide a grammatical approach to developing autonomous generative design systems.

KEYWORDS: Autonomous agents, 3D virtual worlds, design grammars, generative design.

1. INTRODUCTION

Supporting a wide variety of human activities online, 3D virtual worlds are networked environments designed using the place metaphor. 3D virtual worlds distinguish themselves from other networked technologies by having place characteristics. It is not just another communication tool but the ultimate destination where we shop, are entertained and get educated (Kalay and Marx 2001). In the architecture, engineering and construction (AEC) domain, 3D virtual worlds as Computer-aided Design (CAD) tools have shown promising potentials in areas such as design simulation, distant team works as well as interdisciplinary design collaboration. By developing and applying the Generative Design Agent (GDA) model, this paper presents and demonstrates a grammatical approach to autonomous design in 3D virtual worlds. The paper advances the development of 3D virtual worlds beyond design simulation and communication to focus on design generation and automation.

Autonomous design is achieved through the use of GDAs that serve as personal design agents to designers in 3D virtual worlds. The GDA model developed in this research specifies five computational processes for reasoning and designing in 3D virtual worlds: sensation, interpretation, hypothesizing, designing and action. A GDA is capable of sensing and interpreting various design requirements simulated in the virtual world or directly entered by the designer, hypothesizing design goals according to these requirements, and finally generating, simulating and modifying the design in the virtual world to satisfy the goals, on behalf of the designer.

The design component of a GDA is supported by the application of a generative design grammar. The grammatical approach to design enables the use of simple elements (design rules) to describe and generate rather rich and complex designs; provides devices to formally define and analyze existing designs of a known style; and allows new design instances that share the same style to emerge through the alternations of rule applications. On one hand, these grammars serve as the generative force to be applied by the GDAs for autonomous design. On the other hand, each grammar defines coherent stylistic characterizations shared by the designs it generates. For designers, this grammatical approach to autonomous design represents a new approach to assisting and empowering design, but at the same time also imposes new challenges on designers redefining their roles in design.

2. BACKGROUND: DESIGNING IN 3D VIRTUAL WORLDS

Virtual worlds, virtual architecture or cyberspace can be understood as networked environments designed using the place metaphor. Through the use of metaphor, we express the concepts in one domain in terms of another (Lakoff and Johnson 1980). The place metaphor provides a consistent context for people to browse digital information, interact with the environment and communicate with each other. The applications of 3D virtual worlds have expanded from the original internet gaming and military simulation to provide supports for other activities such as electronic institutions, virtual museums, distant education, virtual design studios, and so on. 3D virtual worlds have become an important part of the holistic living environments we inhabit supporting everyday economic, cultural, educational and other human activities.

Technologies for designing virtual worlds have developed over the years supporting multi-user text-based, 2D graphical and 3D virtual worlds. Nowadays, most virtual worlds are visualized using 3D models. Platforms for designing 3D virtual worlds include Active Worlds (www.activeworlds.com), Virtools (www.virtools.com), Blaxxun (www.blaxxun.com), Second Life (www.secondlife.com), and others that have been developed from gaming engines such as Quake (www.idsoftware.com). Maher and Simoff (2000) first characterise the design activities in 3D virtual worlds as "Designing within the Design". Unlike in most CAD systems, designers are also represented within the virtual design. They are called avatars (animated characters). "Designing within the Design" lately became the main idea for exploring and enhancing remote team collaboration in design practice. For global design teams, 3D virtual worlds provide an integral platform that utilises digital communication, design representation, and collaborative modelling. Figure 1 illustrates selected designs in 3D virtual worlds from our recent research and teaching.

FIG. 1: Designs in 3D virtual worlds.

Except for the input and output devices, 3D virtual worlds are implemented entirely in the computer environments. After all, these worlds only comprise of assemblies of computing entities, which can be flexibly programmed and configured. This flexibility makes it possible to consider designing in 3D virtual worlds in terms of dynamics and autonomy. However, current designs in 3D virtual worlds are often limited to static simulations. Our research challenges this conventional use of 3D virtual worlds in design; and presents the GDA model for autonomous design in 3D virtual worlds.

3. BACKGROUND: AGENT MODELS FOR 3D VIRTUAL WORLDS

An increased interest of computational agents has been seen in the recent development of networked applications inspired by the concepts of artificial intelligent and artificial life. In the context of computer science, agents as intentional software systems operate independently and rationally, seeking to achieve goals by interacting with their environment (Wooldridge and Jennings 1995). Unlike most computational objects, agents have goals and beliefs and execute actions based on these goals and beliefs (Russell and Norvig 1995). The increasing interconnection and networking of computers requires agents to interact with each other (Huhns and Stephens 1999). Therefore, the concept of a multi-agent system is introduced with the applications of distributed artificial intelligence.

Examples such as networked gaming environments often associate pre-programmed behaviors with 3D objects to provide run-time interactions. This has allowed some components of the environment to be interactive by performing a fixed set of responses. Instead of ascribing fixed sets of behaviors to 3D objects in a virtual world, Maher and Gero (2002) propose a common agent model (Figure 2) to represent a 3D virtual world as a multi-agent system so that each object in the virtual world can become an agent. With sensors and effectors as the interface, each agent can sense the virtual world, reason about the sensed data, hypothesize goals, and make changes to or act in the virtual world to satisfy the goals. 3D virtual worlds developed using this multi-agent model can self-adapt to suit different purposes. The latest development of agent models for 3D virtual worlds include the motivated learning agent model (Merrick and Maher 2006), agent model for multidisciplinary design (Rosenman et al 2005), agent model for 3D virtual worlds that adapt (Smith et al 2004), and agent model for collaborative design between 3D virtual worlds and conventional CAD systems (Maher et al 2003).

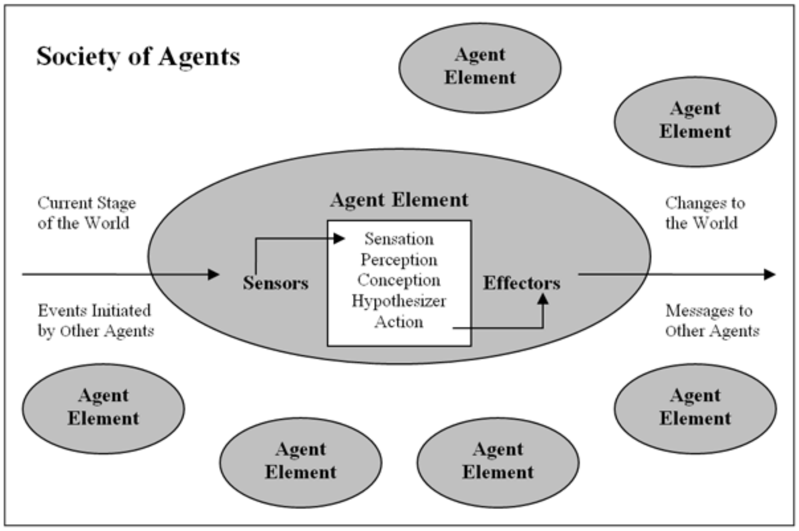

FIG. 2: A 3D virtual world as a multi-agent system (Maher and Gero 2002).

4. GENERATIVE DESIGN AGENT MODEL

Our research takes a different approach from the developments of "object agents" as discussed in Section 3, and proposes augmented design agents for 3D virtual worlds. As a result, the GDA model is developed. The GDA approach provides agencies to the designers in 3D virtual worlds, rather than to the components that make up the virtual design environment. Using this model, each GDA can be associated with a designer and serves as his/her personal design agent in a 3D virtual world. Because the agencies are given to the designers, rather than to existing virtual world components, the 3D virtual world therefore does not need to be pre-defined and design knowledge can be incorporated and managed within each GDA. With appropriate interventions from the human designers, GDAs reason, dynamically and autonomously generate, simulate and modify designs in the 3D virtual world.

The computational processes of the GDA model are specifically developed for reasoning and designing in 3D virtual worlds. Each GDA has the following two main features:

- Reasoning mechanism: a GDA is able to sense the 3D virtual world, interpret design requirements based on the sense data, hypothesize design goals in order to satisfy the requirements, and finally generate, simulate and modify designs in the virtual world as needed according to the goals, on behalf of the designer.
- Design component: a GDA is a design agent. The GDA's design component is supported by the application of a generative design grammar. The concepts and development of generative design grammars are introduced in Section 5.

According to Gero and Kannengiesser (2004, 2002), a situated view of design assumes a non-static environment where the act of designing takes place. Adopting such a view, the process of designing can be modeled as the interactions of three representations of the world: the external world (W_{ext}), the interpreted world (W_{int}) and the expected world (W_{exp}). The external world comprises representations outside the designer. The interpreted world is the internal representation of the external world that exists inside the designer, in terms of his/her knowledge and experience. The expected world is a part of the interpreted world in which the results of designing are predicted based on the designer's current design goals and his/her interpretations of the current state of the world. The computational processes of the GDA model are proposed on the base of Maher and Gero's common agent model for 3D virtual worlds (2002), where sensors and effectors act as the interface between the agent and the 3D virtual world. As shown in Figure 3, there are five computational processes: sensation, interpretation, hypothesizing, designing and action. The external world (W_{ext}), in this case, a 3D virtual world; the GDA's interpreted world (W_{int}) and expected world (W_{exp}) are connected via these five computational processes.

- Sensation: a GDA retrieves relevant raw data from the external world (W_{ext}) to prepare for the processes of interpretation. These data can include any relevant information such as the design brief and context simulated in the 3D virtual world or directly entered by the designer.
- Interpretation: the raw sense data are filtered, focused and transformed to construct the GDA's interpreted world ($W_{ext} \rightarrow W_{int}$), which comprise of the GDA's interpretations of design requirements and the current state of the virtual world.
- Hypothesizing: the GDA sets up design goals that aim to eliminate or reduce the mismatches between the design requirements and the current state of the virtual world ($W_{int} \rightarrow W_{exp}$).
- Designing: the GDA model is essentially a design agent model. To address this design aspect, one of the computational processes of the GDA model is singled out as designing. In the process of designing, the GDA applies its generative design grammar to generate a design or modify an existing design in order to satisfy its current design goals. The design is temporarily stored in its expected world (W_{exp}). Generative design grammars and their applications by the GDAs will be discussed in Section 5.
- Action: the final processes of action include action planning and action activation. The GDA plans actions for simulating the generated design and activates these actions to realize the design in the 3D virtual world ($W_{exp} \rightarrow W_{ext}$).

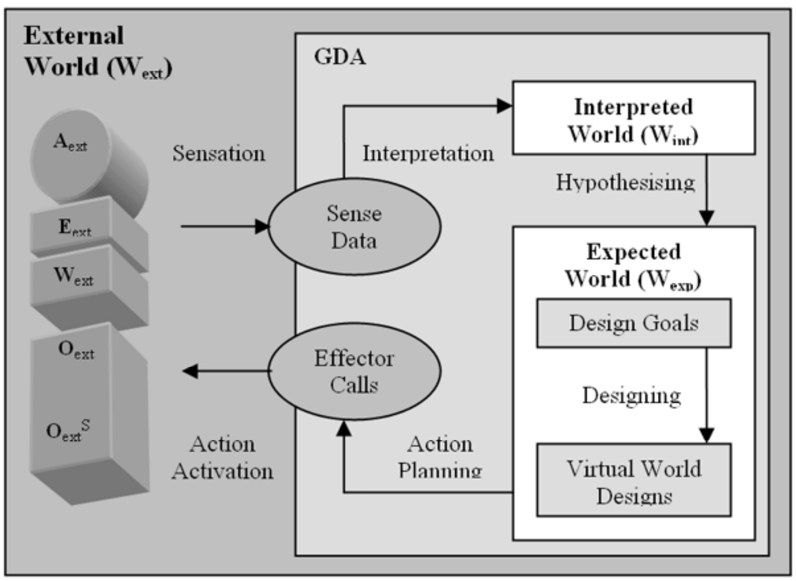

FIG. 3: Five computational processes of the GDA model.

These five computational processes form a recursive loop. Every relevant change in the 3D virtual world will trigger a new round of sensation, interpretation, hypothesizing, designing and action within the GDA. In this manner, dynamic and autonomous design in 3D virtual worlds is achieved.

5. GENERATIVE DESIGN GRAMMARS

The GDA's designing process requires a generative design formalism to produce design solutions, on behalf of the human designer. The concept and development of generative design grammars for this research are inspired by the notions of shape grammars (Stiny and Gips 1972). The inspiration comes directly from shape grammars as a design formalism for describing and generating designs in general. Over the last three decades, the theories and applications of shape grammars have been applied to a wide range of design areas; for example, fine arts, architecture, industrial design, engineering design, design computing and so on.

Knight (2000) summarizes that a shape grammar is a set of shape rules that can be applied in a step-by-step manner to generate a set, or language, of designs. The nature of shape grammars is both descriptive and generative:

- Shapes (points, lines, planes or volumes) as the basic components of shape rules are descriptions of the designs that the grammars generate.
- The applications of the shape rules generate designs via shape operations and spatial transformations.

Inheriting the descriptive and generative nature of shape grammars, our generative design grammars are capable of describing designs in 3D virtual worlds using components of the design rules and generating designs via rule applications. The descriptive and generative qualities of generative design grammars well serve the purposes for designing in 3D virtual worlds.

Generative design grammars are applied by the GDAs to generate designs in the 3D virtual worlds. This section presents a framework which provides guidelines and strategies for developing generative design grammars by defining the general structure of a grammar and the general structure of its basic components: design rules. Using the generative design grammar framework, designers define grammars that produce different design languages for 3D virtual worlds, rather than predefine every detail of all possible designs. On behalf of the human designers, the GDAs carry out the design tasks by applying the grammars during real-time interactions.

5.1 Generative Design Grammar Framework

The structure of generative design grammars is determined by the four general phases of designing in 3D virtual worlds. They are:

- To layout places/areas of the design: each place/area has a purpose that accommodates certain intended activities.
- To configure the places/areas of the design: each place/area is then configured with certain objects which provide visual boundaries of the place/area and visual cues for supporting the intended activities.
- To specify navigation methods: navigation in the virtual design can be facilitated to consider the use of way finding aids for assisting the designers and visitors' in exploring the design in the 3D virtual world.
- To establish interactions: in general, this is a process of ascribing behaviors to selected objects in each place/area of the virtual design so that physical interactions of the design can be simulated or the designers and visitors can interact with the virtual design.

The four set of design rules: layout rules, object placement rules, navigation rules and interaction rules address the above four design phases accordingly. The generative design grammar framework is illustrated in Figure 4. The firing sequence of the design rules follows the order of layout rules, object placement rules, navigation rules and finally interaction rules. Integrated with relevant design and domain knowledge, generative design grammars can be developed by following this general structure. The stylistic characterizations of the generated designs - in terms of the syntax (visualization: layout and object placement) and in terms of the semantics (navigation and interaction) - are defined accordingly in these four sets of rules.

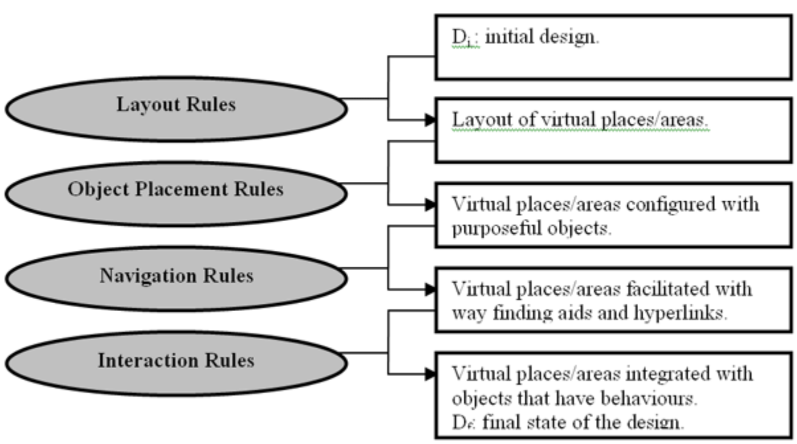

FIG. 4: Generative design grammar framework.

Like shape grammars, generative design grammars also use spatial labels and state labels to control the application of design rules. The original use of state labels in a shape grammar is to control the sequence of shape rule applications. In a generative design grammar, on one hand, this original purpose is maintained so that the designs rules can be applied in the sequence of layout rules, object placement rules, navigation rules and interaction rules. On the other hand, a special set of state labels are developed to represent a set of design contexts that can relate to the GDA's design goals. Using these special state labels, the application of the generative design grammar can be directed to generate designs that meet the current design requirements as interpreted by the GDA.

5.2 Design Rules

Layout rules are the first set of design rules to be fired in the application of a generative design grammar. They are visual/spatial rules that generate the layout of places/areas according to the kinds of activities to be supported, as outlined in the design requirements. Figure 5 illustrates two example layout rules taken from a generative design grammar for a gallery design. By applying the first rule, the design of the gallery will be expanded by adding an additional area. By applying the second rule, the design of the gallery will be changed by subtracting an area.

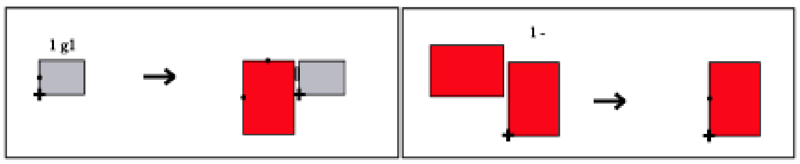

FIG. 5: Two example layout rules.

Object placement rules are fired after layout rules, they are also visual/spatial rules. After a layout is produced, object placement rules further configure each place/area to provide visual boundaries of the place/area and visual cues for supporting the intended activities, through object placements. Figure 6 shows two example object placement rules that generate the visual boundaries for two different areas in a gallery design. Figure 7 shows an example object placement rule that arranges the interior of a display area for exhibition.

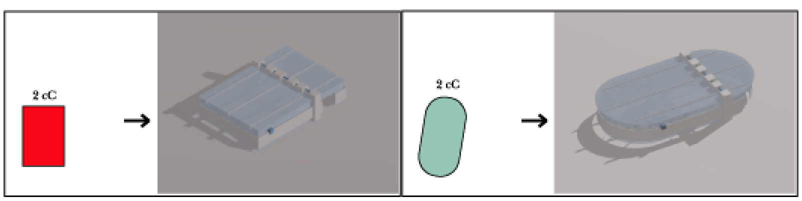

FIG. 6: Two example layout rules that generate visual boundaries for different areas of a gallery design.

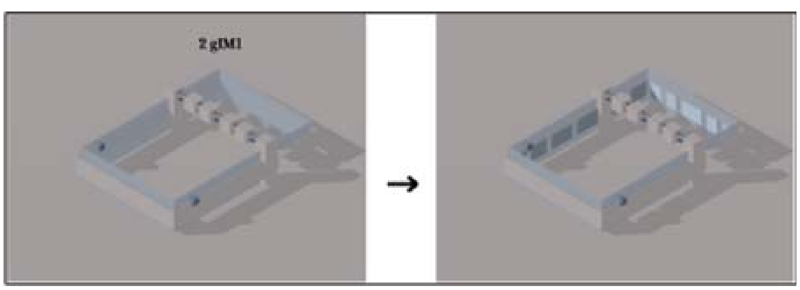

FIG. 7: An example layout rule that arranges the interior of a display area for exhibition.

Navigation rules are fired next in a generative design grammar, after layout rules and object placement rules. Navigation rules provide way finding aids in the generated places/areas to assist the designers and visitors' navigation. Way finding aids can be simulated in 3D virtual worlds with direct references to those in built environments (Vinson 1999, Darken and Sibert 1996, 1993). There are at least two kinds of way finding aids we use in built environments:

- The use of spatial elements; for example, paths, openings, hallways, stairs, intersections, landmarks, maps, signs and so on.
- The use of social elements; for example, the assistance gained from guides or other people.

Besides these way finding aids originating from built environments, virtual worlds also have their unique forms of navigation since virtual places/areas are hyper-linked. Most virtual worlds allow people to move directly between any two locations using hyperlinks. Hyperlinks are not parts of the actual design as they cannot be reproduced in the physical world. However they are important for the design in the virtual world as they often enable designers and visitors to explore the design and the virtual world more efficiently.

Navigation rules are not entirely visual/spatial. The application of the rules indeed involves object placements for defining way finding aids in the generated places/areas. However, before these object placements are made, navigation rules are mainly about recognizing the connections among these generated places/areas and finding appropriate navigation methods for the designers and visitors to access these places/areas. Figure 8 shows the effect of an example navigation rule. The left-hand-side image is the interior of a display area in a gallery design. The right-hand-side image shows that a hyperlink is created and appears as a color stone on the floor. After appropriate behaviors are ascribed, the link will take the designers and visitors to another display area when it is "stepped" on, if they want immediate exit.

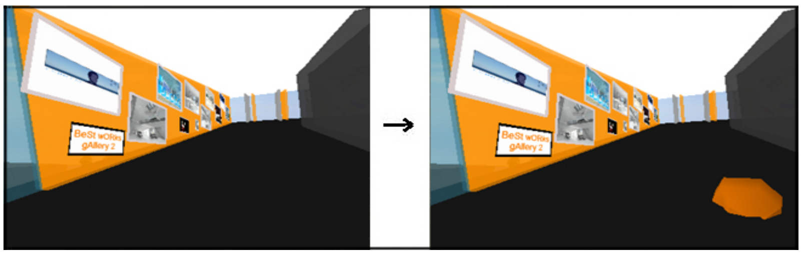

FIG. 8: The Effect of an example navigation rule.

Interaction rules are the final set of design rules to be fired in a generative design grammar. The application of interaction rules ascribes appropriate behaviors to selected objects in each generated places/areas. Therefore, physical interactions can be simulated or the designers and visitors can interact with the virtual design.

Interaction rules are non-visual/spatial rules that recognize selected objects in the virtual design and ascribe appropriate behaviors to these objects. There are two different types of interaction rules. One supplements object placement rules and the other supplements navigation rules. Object placement rules define visual boundaries for each generated place/area and place purposeful objects in the place/area. The first type of the interaction rule ascribes behaviors to relevant objects in order to simulate certain physical interactions in these places/areas. The other type of interaction rule looks for way finding aids and hyperlinks generated by navigation rules and ascribe appropriate behaviors to activate them.

Because interaction rules do not operate on a visual/spatial level they are not appropriate to be expressed using illustrations. In this study, interactions rules are expressed in the form of "IF… THEN…" Without getting into the technical details of ascribing behaviors to 3D objects in virtual worlds, Figure 9 shows the effect of an example interaction rule of the first type for supplementing object placement rules. The left-hand-side image is the exterior of a gallery design with an empty advertisement board. The right-hand-side image shows the same advertisement board displaying digital images in an animated sequence, after the interaction rule is fired, which configures the object properties of the advertisement board object using a scripting language to enable the animation to be shown.

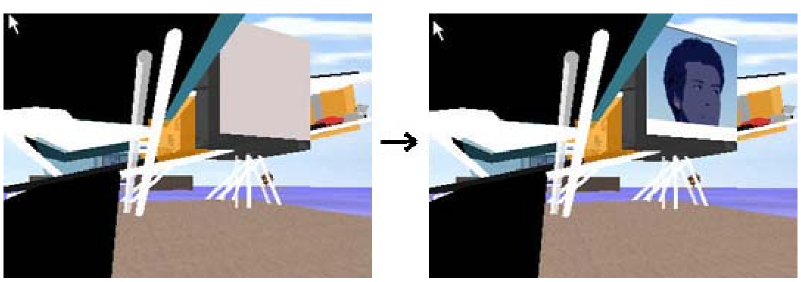

FIG. 9: The effect of an example interaction rule.

6. DEMONSTRATION

This section presents a design scenario of a gallery. This design scenario aims to demonstrate the application of the GDA model and generative design grammars, and their effectiveness for autonomous design in 3D virtual worlds. The design scenario consists of six different stages. The different stages present various changes of design requirements during the designing process; for example, changes of activities, changes of exhibition requirements, changes of gallery capacities, and so on. The scenario shows that a GDA senses these changes of design requirements, either being simulated in the 3D virtual world or entered directly by the human designer. By altering the sequence of the design rule application in its generative design grammar, the GDA dynamically and autonomously generates, simulates and modifies different designs in the 3D virtual world to address different changes of design requirements. In terms of the technical implementation, the GDA is implemented using Java. The scenario is implemented in a 3D virtual world developed using the Active Worlds platform. The design rules of the generative design grammar example, and a general rule base for supporting the GDA's reasoning, are written using Jess (herzberg.ca.sandia.gov/jess), a rule-based scripting language (Friedman-Hill 2003). Figures 10 and 11 illustrate different designs of the gallery, both plans and 3D views in the virtual world, generated by the GDA for the six stages of the scenario.

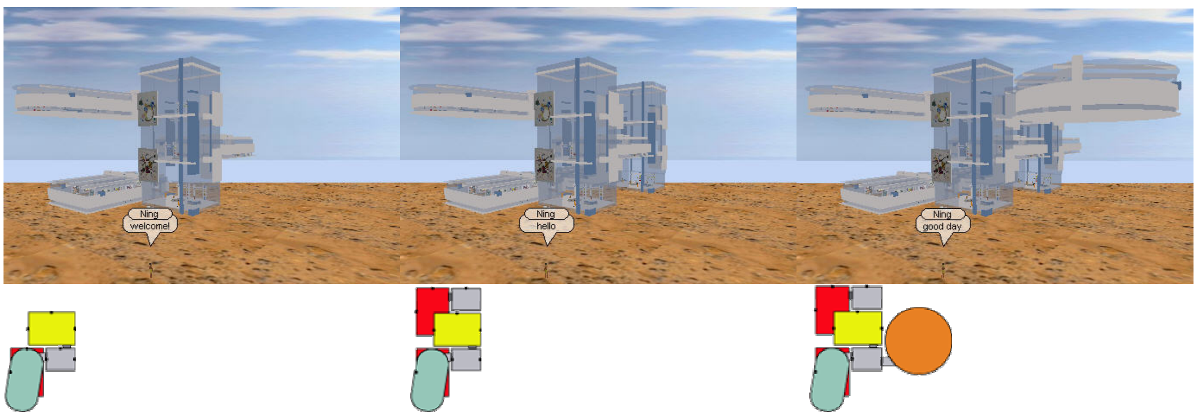

FIG. 10: Plans and 3D designs of a gallery generated for stage 1-3 of the scenario.

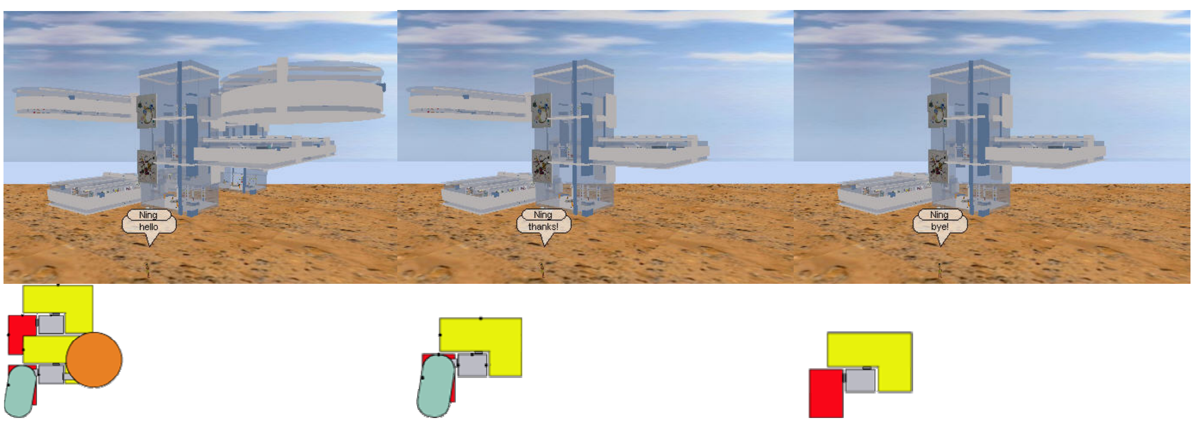

FIG. 11: Plans and 3D designs of a gallery generated for stage 4-6 of the scenario.

In the cases when there is more than one design rule that meet the current design context, a control mechanism is needed to resolve the conflict. In general, there are three main methods for controlling the generative design grammar application. They are random selection; human designer intervention; and agent learning mechanism. This scenario uses the human designer intervention method.

- The random selection method allows the system to randomly select one design rule from the set of rules that meet the conditions.
- The human designer intervention method allows the system to turn to human designers for instructions once such a conflict occurs.

- The agent learning mechanism provide a more dynamic but complex approach to allow the system to resolve the conflict based on the agent's past design experience.

7. CONCLUSION

This paper presents the GDA model and the generative design grammar framework for autonomous design in 3D virtual worlds. The use of GDAs and generative design grammars is demonstrated through a design scenario, where a GDA reasons; dynamically and autonomously generates, simulates and modifies designs of a gallery in a 3D virtual world. Although the design scenario is constructed with a specific kind of gallery design in mind, it demonstrates the effectiveness of the GDA model and generative design grammars both for autonomous designs in 3D virtual worlds. Integrated with different design and domain knowledge, the GDA model and generative design grammars can be applied to autonomous design in 3D virtual worlds for other purposes. Highlighted with the GDA's generative capabilities, this research provides new insights for designing in 3D virtual worlds from the following perspectives:

- The GDA model introduces dynamics and autonomy to designing in 3D virtual worlds. 3D virtual worlds integrated with the GDA model can go beyond the conventional purpose of design communication and static simulation to support design generation and automation. Each GDA is a personal design agent. The agency is applied to assist designers in the 3D virtual world, instead of each structural or spatial component of the virtual design environment.
- The generative design grammar framework serves as a base for developing generative design grammars with different styles that suits different purposes.
- The generative design grammar framework also provides a foundation to formally study the styles of 3D virtual worlds. Compared to other novice designs, virtual worlds designed with a specific style in mind will achieve better consistency in terms of visualization, navigation and interaction, and this consistency provides a strong base to assist the designers and visitors' orientations and interactions in 3D virtual worlds.

This grammatical approach to autonomous design in 3D virtual worlds using GDAs and generative design grammars also highlights the following advantages:

- The use of rational design agents presents a robust approach to design reasoning , generation and automation. These design agents are intentional systems that operate independently and actively seek to satisfy their design goals to meet the changing design requirements, by interacting with the 3D virtual world.
- 3D virtual worlds not only visualize the generated designs. More importantly, they serve as a platform for representing design requirements as well as simulating contextual information that affect the designing process.
- The use of generative design grammars provides a formal framework to describe and generate designs with stylistic considerations.
- Designers do not repetitively produce individual designs. Instead, they specify design grammars for the GDAs. The application of the design grammar then is directed by the actual design requirements, to dynamically and automatically generate individual design instances in 3D virtual worlds. This will require designers to gain a different set of skills to understand and accommodate grammatical approach to design.

The future extension of this study will be focused on agent communication and collaborative design. The first research direction is to study the GDA's interpretation and designing processes in a more complex multi-GDA 3D virtual world. The second research direction is to study the collective design styles shared by a society of GDAs.

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