

The Algorithmic Beauty of Cities

Interactive Modeling and Realtime Visualization of Compact Procedural Descriptions

Von der Fakultät für Mathematik, Informatik und Naturwissenschaften der
RWTH Aachen University zur Erlangung des akademischen Grades eines
Doktors der Naturwissenschaften genehmigte Dissertation

vorgelegt von Diplom-Informatiker

Lars Krecklau

aus Düsseldorf, Deutschland

Berichter: Prof. Dr. Leif Kobbelt

Prof. Dr. Michael Wimmer

Tag der mündlichen Prüfung: 27.05.2013

Diese Dissertation ist auf den Internetseiten der Hochschulbibliothek online verfügbar.

Selected Topics in Computer Graphics

herausgegeben von
Prof. Dr. Leif Kobbelt
Lehrstuhl für Informatik 8
Computergraphik & Multimedia
RWTH Aachen University

Band 10

Lars Krecklau

The Algorithmic Beauty of Cities

Interactive Modeling and Realtime Visualization
of Compact Procedural Descriptions

Shaker Verlag
Aachen 2013

Bibliographic information published by the Deutsche Nationalbibliothek

The Deutsche Nationalbibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data are available in the Internet at <http://dnb.d-nb.de>.

Zugl.: D 82 (Diss. RWTH Aachen University, 2013)

Copyright Shaker Verlag 2013

All rights reserved. No part of this publication may be reproduced, stored in a retrieval system, or transmitted, in any form or by any means, electronic, mechanical, photocopying, recording or otherwise, without the prior permission of the publishers.

Printed in Germany.

ISBN 978-3-8440-2133-2

ISSN 1861-2660

Shaker Verlag GmbH • P.O. BOX 101818 • D-52018 Aachen

Phone: 0049/2407/9596-0 • Telefax: 0049/2407/9596-9

Internet: www.shaker.de • e-mail: info@shaker.de

Abstract

Today's world is full of synthesized digital media like high quality renderings in form of images or movies and real time visualizations of complex environments in form of fully interactive applications such as games. Present rendering algorithms allow for the production of synthetical images that are hard to distinguish from pictures which were taken from the real world. Even with commodity hardware, high quality renderings can be finished in reasonable time. Consequently, there are many applications in practice which benefit from virtual environments. For example, many film productions use digital copies of real world locations like famous cities to easily include artificial content (e.g. crowds of people), to allow for complex camera trajectories (e.g. falling from the sky to the street level), or to simulate large scale effects (e.g. a heavy destruction of the scene). This digest of new possibilities would be very expensive or even infeasible without using virtual scenes.

One of the biggest bottlenecks in the production workflow of films and games is the content creation. The modeling of large scale virtual environments that provide a high amount of detail is a time consuming and sometimes tedious task. The problem is often compensated by just keeping a high number of artists busy, however, this solution is rather expensive and requires a lot of organisational overhead. Unfortunately, content creation is a creative task and thus, it can not be fully automatized, i.e. the visionary input of artists is still needed. This thesis is focused on the generation and rendering of cities including common entities like buildings, bridges, and plants. Instead of rationalising the work of artists, we rather aim at the development of supportive tools that utilize the expressive power of procedural modeling techniques combined with easily operated user interfaces for the intuitive and efficient insertion of creative input.

The novelties of this thesis are categorized into three parts dealing with the theoretical background of procedural modeling techniques, the interactive extensions for algorithmically generated content, and the real time visualization of compactly described virtual city models.

In the first part, the fundamental formalisms of procedural modeling techniques are discussed and analysed with respect to their application in virtual environments. An expressive but yet intuitive modeling language is presented that allows for the combination of several existing modeling strategies and thus, enables the creation of hierarchical structures (e.g. buildings and plants) as well as of interconnected structures (e.g. bridges and power poles) within one unified description. One major advantage for such a unified language is the easy interoperability of different object domains. For example, the growth process of an ivy plant is controlled by high-level semantics of the scene, i.e. the branches tend to grow towards the closest stone elements defined, e.g., by the walls of a building. In addition to statically defined geometry, an algorithm for producing plausible animations of the city development is introduced. In contrast to other approaches relying on a complex mathematical model to extrapolate a given street network into the near future, the presented method procedurally interpolates inserted real world data based on fuzzy information taken from historical city maps and books.

The second part of the thesis presents interactive extensions to the previously developed modeling language. Most importantly, there are two different views on the system. On the one hand, the presented method allows for interactive scripting combining conventional modeling tasks (i.e. creating, transforming, and manipulating geometrical shapes) with the power of procedural modeling (e.g. automatically apply the same operations on several instances of the same object). Although this is a supportive tool for artists, it still requires modeling and sometimes even scripting skills. On the other hand, procedural objects are enhanced with a set of intuitive parameters that can be manipulated in a 3D viewer. Consequently, the user never gets in touch with the underlying grammar. Having a database of self-contained procedural layouts and objects, an intuitive interface is presented that enables the fast combination and manipulation of existing elements, even for users without scripting or modeling experience.

In the third part, the efficient rendering of large scale procedural city models will be discussed. Taking a coarse polygonal model of a city, i.e. extruded floor plans, high quality textures of the facades are generated on-the-fly. This is extremely beneficial for large scale models, since the theoretical amount of data never needs to be stored explicitly. The presented algorithm evaluates the facade grammars on a per-pixel basis supporting a stochastic rule set, multiple layers, and the raytracing of 3D rooms. Furthermore, an efficient screen space method for geometry instantiation is proposed to enhance the visual quality of the rendering by additional real 3D polygonal geometry. We demonstrate our technique on a large and highly detailed city model achieving real time framerates.

Acknowledgements

First of all, I would like to thank my doctoral advisor Leif Kobbelt for his productive support and his innovative ideas. It was a great pleasure to work with him, one of the most famous professors in the computer graphics community.

Furthermore, I would like to thank my co-examiner Michael Wimmer for his motivating comments on my conference presentations and his trust in my work.

Moreover, I would like to thank all current and former members of our chair for being supportive colleagues and good friends. Special thanks go to my co-authors: Darko Pavic, Christopher Manthei, and Janis Born, who did a great job contributing to this work. Further special thanks go to my student assistants: Andreas Neu and Sebastian Landwehr, who steadily pushed and maintained a couple of interesting research projects.

In addition, I would like to thank Arne Schmitz for his advanced Python and Blender support, Dominik Sibbing for the joint development of the award-winning poster about city virtualization, Robert Menzel for the joint organization of the first gamescom booth representing the work of our chair, Ming Li for the cooperative supervision of the practical courses, Jan Möbius for fastly processing all arising administrative tasks, Hans-Christian Ebke and Marcel Campen for the realization of the most outstanding TDI (Tag der Informatik) in the history of the RWTH, and David Bommes, Martin Habbecke, Ellen Dekkers, and Henrik Zimmer for their creative input at our monthly "Geometry-Stammtisch". Special thanks go to my close friends Sara Knabe and Markus Roth who provided a great image of the Grand Canyon for the related work section of this thesis.

Finally, I would like to thank my family and close friends for their patience and their emotional assistance. I would particularly like to thank my girlfriend Mirte Ronda, my mother Hannelore Krecklau, my father Detlev Krecklau, my stepmother Andrea Pillen-Krecklau, my sisters Anika Lysko-Krecklau and Charlotte Krecklau, my brother-in-law Jakub Lysko as well as my best friends Stephan Günnemann, Christian Rensing, Kenji Honma, Michael Gubesch, and Roman Kuhl for always reminding me of the most important values that make life worth living.

Contents

- 1. Introduction** 1
- 2. State-of-the-Art** 7
 - 2.1. Geologic Phenomena 9
 - 2.2. Vegetation 13
 - 2.3. Architectural Structures 21
 - 2.4. Street Networks and Cities 33
 - 2.5. The 4th Dimension 39
- 3. Contributions** 43
- I. Formalizing Cities** 47
- 4. The Design of a Modeling Language** 51
 - 4.1. System Features 52
 - 4.1.1. Classes and their Attributes 53
 - 4.1.2. Operators and their Attributes 54
 - 4.1.3. Dynamic Modules 57
 - 4.1.4. Abstract Structure Templates 58
 - 4.1.5. Tags 59
 - 4.1.6. Containers 61
 - 4.1.7. Depth First Evaluation vs Breadth First Evaluation 62
 - 4.2. From General-Purpose to Domain-Specific 64
 - 4.2.1. Basic Hierarchy 64
 - 4.2.2. The System 65
 - 4.2.3. The Grammar 68
 - 4.2.4. The Syntax 70

4.3. Hierarchical Structures	72
4.3.1. Modeling Strategy	73
4.3.1.1. Boxes	74
4.3.1.2. Trilinear Free Form Deformation Cages	74
4.3.1.3. Trilinear Free Form Turtle Graphics	76
4.3.2. Results	77
4.3.2.1. Architectural Modeling	78
4.3.2.2. Plant Modeling	82
4.4. Interconnected Structures	84
4.4.1. Concepts	85
4.4.1.1. Modeling Curves	85
4.4.1.2. Inverse Kinematics	87
4.4.2. Modeling Strategy	89
4.4.2.1. Containers	90
4.4.2.2. Determining Connection Pairs	91
4.4.2.3. Generating Interconnection Geometry	93
4.4.3. Results	96
4.4.3.1. Deformable Beams by Shooting	97
4.4.3.2. Rigid Chain by Shooting	98
4.4.3.3. Rigid Chains by Fixed Patterns	98
4.4.3.4. Catenary in a Street	100
4.4.3.5. Sydney Harbour Bridge	100
4.4.3.6. Power Poles	104
4.4.3.7. Roller Coaster	106
4.5. Discussion	108
5. The 4th Dimension	111
5.1. Procedural Interpolation of Historical City Maps	113
5.1.1. Events	114
5.1.2. Land Use Maps	115
5.1.3. Simulation	116
5.1.3.1. Dependencies	117
5.1.3.2. Lower and Upper Bounds	118
5.1.3.3. Score Rules	121
5.1.3.4. Histogram	122

5.2. Information Authoring	124
5.2.1. Shape Modeling	124
5.2.2. Land Use Maps	124
5.2.3. Timeline Editing	125
5.2.4. Historical City Maps	126
5.3. Results	127
5.3.1. City Development of Austin	128
5.3.2. City Development of Aachen	128
5.3.3. Artificial Example	130
5.3.4. Animation Comparison	131
5.4. Discussion	132
 II. Intuitive Procedural Content Creation	 135
 6. Interactive Scripting	 139
6.1. Integrating Code with GUI Elements	140
6.2. Encapsulation of Interactive Procedural Objects	142
6.2.1. Parameter Manipulators	142
6.2.2. Camera Views	144
6.2.3. Prototypes	145
6.2.4. Compound Primitives	146
6.3. Discussion	148
 7. Intuitive Composition	 149
7.1. The Toy-Block Principle	149
7.1.1. Replacement	150
7.1.2. Parameter Adjustment	151
7.1.3. Local Modifications	152
7.2. Results	153
7.2.1. Buildings	153
7.2.2. Furniture	154
7.2.3. Plants	156
7.3. Discussion	158

8. User Study	159
8.1. Setup	159
8.2. NASA-TLX	160
8.3. Questionnaire	161
8.4. Discussion	161
III. Visualization of Procedural Cities	163
9. Realtime Compositing of Procedural Facade Textures on the GPU	167
9.1. Operators	170
9.1.1. Subdivision	170
9.1.2. Stochastic Variation	172
9.1.3. Layers	173
9.1.4. 3D Rooms	175
9.1.5. Material	176
9.2. GPU Representation	176
9.3. Results	179
9.4. Discussion	181
10. Realtime Rendering of Procedural Facades with High Geometric Detail	183
10.1. Pixel Driven Geometry Instances	185
10.2. Attachment Scopes	185
10.2.1. Detail Object Instantiation	186
10.2.2. Duplication Prevention	188
10.2.3. Visibility Artifacts	190
10.2.3.1. Attachment Scopes on Back Faces	190
10.2.3.2. Attachment Scope Occlusion	193
10.2.3.3. Attachment Scopes Outside Screen Space	193
10.3. Attachment Textures	194
10.3.1. Detail Object Instantiation	195
10.4. Results	197
10.4.1. Brickwork	197
10.4.2. Ivy	198
10.4.3. Historical Facades	199
10.5. Discussion	201

11. Conclusion	205
Bibliography	209
Computer Graphics Forum - Cover Competition	223