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Interactive Modeling and Visualization of Virtual Urban Spaces

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Abstract

In this overview paper the main techniques used in procedural modelling of architecture (buildings, facades) are described. This is a relatively new and wide interdisciplinary field, which is growing very quickly, mainly in the last ten years. We discuss important publications focused on procedural techniques like L systems or shape grammars and their usability in procedural architecture creation. Then, we introduce essential articles on procedural modelling of cities and we also include ideas from papers specialized in generation of buildings, facades, architectural structures and related city components. Finally, we focus on interesting computer vision techniques in architecture reconstruction and their connection to formal languages. Our aim is to demonstrate that the procedural city modelling needs to integrate specially modified computer vision algorithms in order to achieve a higher degree of realism and a wider acceptance in various professional application areas.

Key Words

Procedural modelling, grammars, computer vision, architectural styles, buildings

1. Introduction

Procedural modelling is somewhere in between hand-made process (with full control) and physically based simulation (weak result control). It is based on code segments or algorithms that specify some characteristics of a computer-generated model or effect. Procedural modelling refers to a wide number of techniques for automatic creation, often defined by a small input set of data that describe the properties. The actual object is constructed by a procedure that may use randomness to add variety. Procedural modelling offers a degree of flexibility and is used to generate models that are too complex. At first, it was practiced mainly for natural objects such as trees, mountains, clouds [1]. Nowadays, it is also frequently applied for creation of man-made objects such as buildings and whole cities. Examples of these can be found in [2], [3], [4] and others. Procedural creation of cities and urban environments is very useful in movie industry, computer animation, in game development or in simulation and visualization. The main advantage is a fast generation of complicated and large environments without a big amount of manual labour and therefore with a low price [4]. Although procedural modelling is a very powerful paradigm, small changes of the parameters can cause huge changes in the resulting model, which may not be plausible anymore [1]. Procedural modelling is useful mainly for creating objects that have repetitive parts. As an example, we have many similar buildings in the city. Generally, a building has a number of the same windows and ornaments. When we exaggerate, a single building shape with different parameters can model an entire city.

In computer vision, we can reconstruct buildings from photographs, aerial images or video sequences, either semi automatically or fully automatically. In reconstruction of facades, a symmetry and repetitive appearance of structures like windows are often utilized. Such knowledge also helps in making rules for formal languages used for further procedural modelling. This creates an interdisciplinary connection between computer vision and modelling. There are examples of intersection of these disciplines. An article written by Vanegas et. al. [5] is oriented only on Manhattan world objects. Another paper by Becker and Haala [6] is about reconstruction of building facades from terrestrial laser scanning supported by grammar. Nevertheless, none of these works is oriented particularly on computer vision techniques for procedural modelling of architectural styles in general. In our paper, we show that such interdisciplinary connection is not only possible, but is a key for efficient creation of highly realistic computer generated cities.

2. Theory Overview

The procedural modelling of cities started in 2001 by Yoav Parish and Pascal Müller [2]. Many papers then followed, in 2003 about instant architecture [3], in 2005 in the field of cultural heritage [7], in 2006 about buildings creation [4]. Later, there has been a “boom” in publishing works about procedural modelling of cities and their components with different aim. At Eurographics 2009 an overview of procedural modelling of cities in general was summarized [8]. Authors wrote about architecture creation in context of whole city generation. They grouped urban modelling methods according to field (layout, building and facade modelling). They show several examples in image based procedural modelling, but they do not talk about connection between procedural modelling and computer vision. Compared with this article, our paper is not focused on whole city generation, but only on small part related to building architecture and to the connection between procedural modelling and computer vision, which has not been discussed in any overview paper yet.

2.1 Procedural Techniques for City Modelling

In this part, we describe key procedural techniques (L systems, CGA, split grammars), their original goals and their usage in city or buildings creation.

Lindenmayer systems have a long history in computer graphics. From the modelling and simulation of different plant types [9], L-systems have been extended over the time with environment sensitivity and interaction. Complex ecosystems have been modelled, where L systems have been used not only to generate plants, but also to model their distribution. Nowadays, L-systems are used in procedural modelling of cities, for example in automatic street graph construction [2].

Shape grammars were introduced in 70’s by Stiny and Gips [10]. They were traditionally operated on arrangements of objects in two dimensions. In procedural modelled cities, a 3D version is used, but theoretically, n dimensional is possible. Rules specify shapes and also the manner in which they are replaced. Input shapes can be replaced with zero or arbitrary number of shapes in every iteration [3], [8], [10].

A shape grammar called Computer Graphics Architecture (CGA) was introduced in 2006 especially for urban and architectural scenes creation [4]. The CGA is specified to generate architectural 3D content and is used in CityEngine system [11]. The idea of this grammar-based modelling is to define rules that iteratively derive a design of object by creating more and more details. Rules operate on shapes that consist of geometry in a locally oriented bounding-box (scope).

Split grammars, presented at Siggraph 2003 by Peter Wonka et al. [3], are a specialized type of grammar operating on shapes. “Split” means the decomposition of a basic shape into shapes from the vocabulary. The modelling process of a spatial layout of a building is divided by splitting rules to elements, which are recursively split into windows, decorations, etc. In this approach, there is also control grammar, which interacts with a split grammar and set attributes. In the “instant architecture” solution, the final facade is 3D shape with many details [3], [12].

Style grammars were published by Daniel Aliaga et al. in 2007 [13] and they were used for inverse procedural modelling of buildings in the same style as input architecture. Buildings are represented hierarchically by production rules and terminals.

All of these approaches are different and every of them has some pros and cons. Different grammars are more suitable for different goals, for example, split grammars are useful mainly for rectangular structures – facades. There is an overlap of techniques, for example, CGA grammar was inspired by the idea of L-systems and also split rules. However, a construction of grammars covering a variety of building shapes and styles remains an open issue.

3. Architecture and Procedural Modelling

In this section, we focus on the hierarchy of urban area in common view and in semantic context with highlighting of the time dimension. Our main stream is in the procedural modelling of architecture. In our structure (see section 3.1), procedural modelling of architecture is defined as subset of issues related to cities generation. In this new model, we understand architecture creation as a procedural generation of facades, mass models or their inside structure. Next to these issues, we discuss possible input parameters in creation of formal rules for architecture. Last part is given to cultural heritage point of view of generated data, i.e. to processing historical architectural styles.

3.1 Structure of Urban Areas

There is a common view on structure of urban spaces in procedural modelling, in figure 1, a general pipeline is illustrated, according to paper [8]. This scheme was, for example, used in system called CityEngine [2] that is capable of modelling a complete city using a small set of input data – geographical (elevation, land, water, vegetation distribution), socio-statistical maps (population density, residential, commercial or mixed zones, street patterns, maximal house height). System is controllable by the user and there are three main parts of city creation: street network modelling, buildings creation and finally, facades generation. In this approach, the streets are the main elements in hierarchy defining the structure of final model. Minor roads are branched from major roads. Blocks, which are divided to lots, are created according to them. Alternatively, an existing city layout can be completely set as an input.

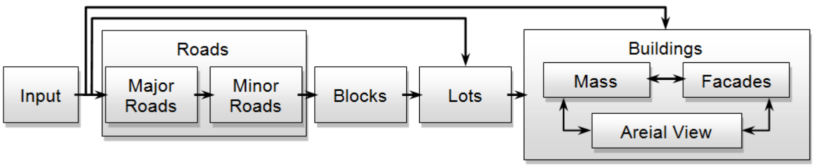

Figure 1: General pipeline for modelling urban areas according to [8].

We introduce different approach how to understand the structure of urban area in space and time. Our view on generation of cities is based on semantic view of city and is different from the general model. We present this view in rough scheme (figure 2). In this figure, relations between parts of urban environment in procedural modelling are presented. This approach is based on hierarchy according to semantic description of parts of the city and its surrounding.

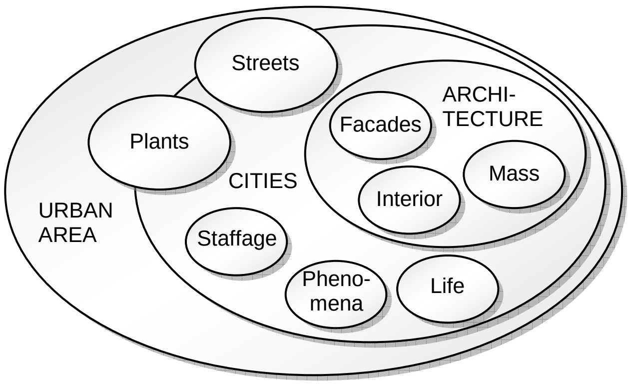

Figure 2: Our vision of structure of procedurally modelled urban area and its parts.

All of the following parts are integrated into the urban space. Roads and paths are inside cities but they also connect towns in smaller or larger urban context. For this reason, streets are visualised on the boundary of city in our scheme. Similarly, plants can be located also outside the city. Parts of cities creation are streets, plants and staffage (lamps, banks etc.). There is also a subset with life elements (crowds or traffic simulation) and their integration into the city. We can include various phenomena (like weather or pollution) into a process of city modelling. There is also architecture, which includes facades, interiors and building shapes generation.

When modelling an urban area, according to figure 1, it is important to choose a part in which we are interested in (for example only facades or whole urban area). In this paper, we concentrate primarily on the architecture. Then, we set where in real world our region of interest is located (GPS, country, altitude level). Now, we have coordinates in space and we can set the point on the timeline (when it was built, respectively time in which we are seeing the object). There is a possible extension of the structure to 4D (objects are changed through time period). The time is necessary for successful simulation of city variability in the relation to architecture, because the architecture changes among town parts built in different time. This all is important for us, because when we are creating formal rules for urban area or its part, we should know the behaviour and the hierarchy of the system. This approach has an advantage in possibility of usage additional information in creation of rules for different architectural styles (see section 3.2).

3.2 Architecture and Formal Rules

In urbanism or architecture there is a different ratio of randomness and regularity than in nature-created objects. Procedural modelling can be applied to both, but in slightly different ways, although there is a view on architecture that sees it as a living organism. We will, however, work with architecture as a man-made object, which obeys mainly human rules and just minimally rules of nature.

During the centuries, architecture has been changing, so every architectural style can be understood as a mirror of the specific time period. Each style has its own rules, construction materials, typical features, characteristic parts and shapes. There are differences in segmentation and fractal dimension of facades from different historical eras. For example, these parameters are considerably different on modern and baroque buildings. This knowledge can be formalised and used in procedural modelling of architectural styles. Definitions of styles and descriptions of specific differences in buildings created for diverse purposes (religious or secular) can be found in encyclopaedia of architecture [14]. Differences are also in the same styles, depending on countries. For example, gothic buildings in continental

Europe and in England are distinguishable on first view. This implies a theory that appearance of building provides us partial information about century, country of formation as well as on owners, builders or architects, and vice versa. We can utilize these facts as input parameters in procedural architecture creation. For example, users set as input parameters that a building was created in the first half of 15th century in Italy as university building and the procedural system will generate possible variations of corresponding model.

However, there is a problem in this approach – many buildings are changing in time. We believe that reconstructions or rebuilds are more often visible on larger scale buildings than on smaller ones. Important aspect is also that footprints and silhouettes of the same type of objects (from different centuries) are similar. For example, church towers have slightly different shapes in detail (which depends on country, century of creation, architectural styles), but they have mainly the same rough characteristics (thin and tall, narrowing to top), which clearly distinguishes them from other types of architecture or buildings for other purposes. Another configurable property of appearance is symmetry of footprint. Mainly, when there is a lot of place, the footprint is symmetric (manor-house). On the other hand, an adaptation to natural environment (for example castles on rocks) implies an asymmetric footprint. The layout of street network has also been changing through history and sometimes this influences the arrangement of buildings and their shapes. This all leads to a possibility to create and use the properties (depending on geographical area, historical period, culture) as the input into the formal rules in 3D city generation.

In the next part we introduce two ideas for creation rules and their parameters in procedural modelling of buildings in specific architectural style. In figure 3, a grammar for one architectural style is created from 3D input (or 2D images processed by computer vision techniques) by inverse process. Input is a representative building of this style and additional information are used only as parameters for generation of different models. In figure 4, there is additional information used as input to inverse process for more specific rules creation.

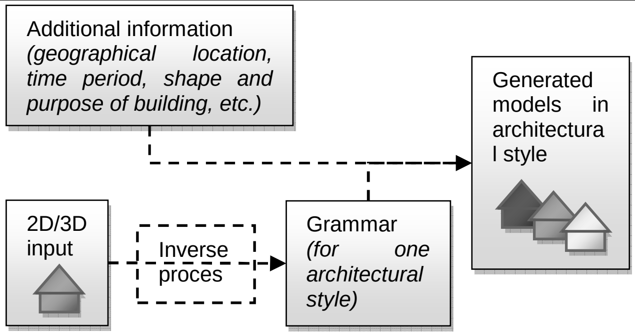

Figure 3: First possibility of usage additional information in procedural modelling

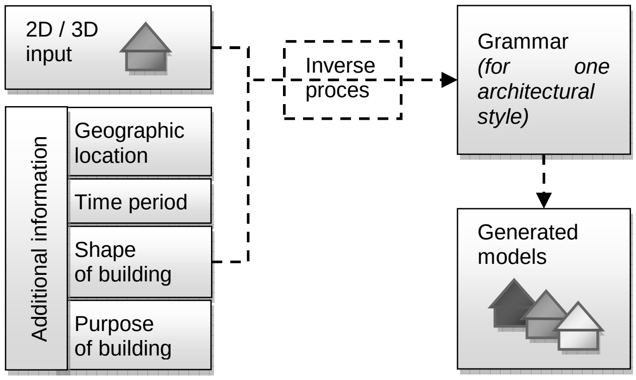

Figure 4: Another possibility of usage additional information in procedural modelling

Similar idea was presented in [15]. The main concept is as follows: User can choose year, one or more architectural styles (and their percentual share in final model), city size (small or large), terrain (flat or another) and the output is model of a city with requested properties. Currently, their implementation is based mainly on randomness while influence among different cultures is not implemented. We see this as work in phase of preparations.

3.3 Cities in time

The time in cities is mainly expressed as a simulation of city behaviour with drastic geometric simplifications and aggregation [16]. We are more interested in visual appearance of the model than in the city behaviour, like traffic simulation, jobs distribution, etc. For this reason, the main interesting works are those focused on geometry modification [16], [17] or simulation of building aging [18].

Weber et al. [16] and similar work [17] simulate the evolution of whole city based on the city behaviour simulation. They simulate the city grow from main streets up to buildings. The building size (building envelop regarding to [16]) is computed based on parcel size and price. If the price is much higher than the current building, the building is replaced by bigger/higher building (i.e. the small buildings in the town centre are replaced by skyscrapers). From our point of view, there is one main drawback in this approach. The newly added building does not respect new architectonical style. The buildings in the start of simulation look similar to the new ones build after 50 years.

Another time enrichment of the model can be achieved by simulation of building aging, as is weathering pollution [18], [19]. These works are from the field of photorealistic image synthesis, so they are not interesting from the procedural modelling point of view but we can imagine the connection where parameters for those effects are procedurally generated. For the real-time rendering, the new material properties can be baked to the texture and animated.

3.4 Cultural Heritage

A specific area is a modelling of historical sights. Procedural techniques are also used in cultural heritage projects, for example they were successfully applied in automatic reconstruction of roman housing architecture [7], or virtual 3D restoration of the Puuc-style buildings in Xkipché [20]. An overview paper “Procedural Modeling for Digital Cultural Heritage” [21] is also written on this topic. The useful feature of procedural modelling in this field is a possibility of quick visualization of multiple reconstruction hypotheses – the same set of rules with other parameters. Sometimes, a strategy that the significant landmarks are modelled manually and whole city is then generated procedurally is applied. In general, procedural approach seems to be very promising in this area.

4. Formation of the architecture

In the previous sections, the procedural modelling and the connection to architecture were described. The ideas about connection of formal rules, architecture, space and time were discussed, and in the following sections, technical aspects of it are presented.

The next sub-sections are organised as follows: The techniques for a procedural generation of buildings are discussed, followed by a description of grammars derivation from already existing models or images that is called inverse procedural modelling. It is an important topic, because the direct creation of grammar rules is hard if we want to define a specific architectural style. Then, techniques used for 3D reconstruction of real buildings are discussed, which are used as an input for inverse modelling. The section is closed by connection between procedural modelling and computer vision, where another usability of formal rules is shown.

4.1 Procedural Modelling of Buildings

Paper written by Pascal Müller et. al. [4] deals with procedural modelling of buildings. The authors combine two ideas – to generate large-scale city and to create detail urban environment. For this goal, they have invented CGA, a shape grammar for the procedural modelling of computer graphics architecture (see section 2.1). The main advantages of this grammar are no restrictions to axis aligned shapes and context sensitive rules. The facade structure is created from the initial shape (mass model) according to rules. Authors with context sensitive rules technique eliminated unwanted intersections of architectural elements [4], [11], in comparison with previous works. The resulting model is generated with all the details, but rules cannot be generated automatically in specific architectural style.

Other approach presented in [22] focuses on architecture modelling with rule assistance. Authors describe an interactive approach called RAAM (rule assist architecture modelling). Authors claim that user does not need to enter all modelling parameters, because many of them can be calculated from sizes of other components. Rules are there used for reducing user interaction and user can of course modify predefined rules. They demonstrated their solution on two types of buildings - villas and dormitories, but presented models do not have many details.

In the paper on “Interactive Visual Editing of Grammars for Procedural Architecture” [23], Lipp et al. introduce a real-time interactive visual editing paradigm for shape grammars, allowing the creation of rule-bases without text file editing. Designing and editing rules is possible by a graphical user interface, but there is still a lot of manual work required when working with the system.

Paper “Procedural Modeling of Structurally-Sound Masonry Buildings” [24] introduced method based on different ideas. Generated models (figure 5) have an inside structure, not only outside shape, which allows the user to simulate a physical interaction with object. In this case, the architectural style and logical structure of building is more important than in other approaches.

Figure 5: Structurally-sound masonry building [24].

4.2 Inverse Procedural Modelling

According to [25], inverse procedural modelling is an automatic generation of procedural rules. The goal is to find the rules of a procedural system that would generate a given model [25] and various secondary models. When we have rules, we can change them for creation of similar objects. In this paper authors described inverse procedural modelling in general. Authors solved this problem only in 2D, by method for clustering of transformations on L systems.

In paper "Style Grammars for Interactive Visualization of Architecture" [13] inverse procedural modelling of buildings was used. The method is based on knowledge that a typical building contains a regular structure. The pattern is automatically detected and used for grammar construction, see section 4.3.

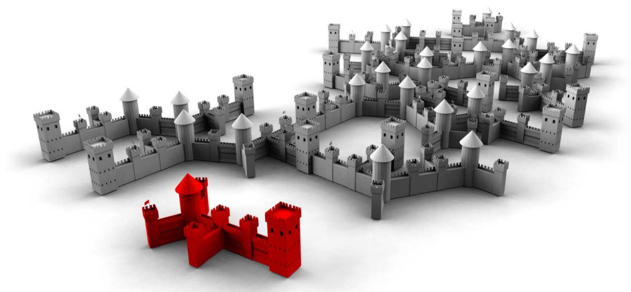

Figure 6: The input model (red castle) and automatically generated model (gray battlement) based on partial symmetry of original model [26].

Paper by Bokeloh et al. [26] is focused on inverse procedural modelling of buildings. Authors used a partial symmetry and similarity of objects for creating rules. Their technology is able to create rules for generation of interesting models (figure 6) even from point clouds.

4.3 Reconstruction of Architecture

The generation of realistic and natural architecture is conditioned and limited by the grammar which is hard to directly define. It seems to be natural to derive the grammar from real objects or their 3D representations. In this section, the reconstruction methods with connection to procedural modelling are described. In these fields, methods reconstructing large urban areas from aerial images and facade reconstruction methods using images from man perspective are mainly studied.

In the procedural modelling of cities [2] it was stated out that building is placed at each lot (one building parcel). The buildings are generated using parametric, stochastic L-system. Similarly, the library of parametric models can be used, which can bring variability to the final model. The parametric building models are mainly generated based on a Digital Elevation Model (DEM), which is obtained by range scanning from planes or satellites. One of the first works about parametric model reconstruction from DEM was published by Weidner and Förstner [27]. They can reconstruct only two types of rectangular building with flat or symmetric sloped roof from DEM. On the other hand, the latest works presented by Lafarge et al. [28], [29] are able to reconstruct variable buildings. They have used a large library of parametric models which are combined together to represent various building types. The parametric models are optimized to best fit DEM data. One of Monte Carlo algorithms with simulated annealing is used for model optimization. The main disadvantage of model reconstruction from DEM is in low resolution of final geometry, mainly there is no reconstruction of details in sizes of 1 meter, like windows and doors. Müller et al. [30] found details even at low resolution images if there is a repetitive facade.

The facades reconstruction is connected with image-based modelling in many works. We can mention the interesting work of Müller et al. [30] where the facade structure (and grammar rules) is automatically generated from one image while the detailed architecture elements are found in the library. This work specialized on enhancing already created 3D models with more realistic facade. The Müllers work is limited to simple repetitive facades. The extension of Müllers work on more generic facades and on the data from street-view was presented by Xiao et al. [31].

Becker and Haala [6] automatically create facade from LiDar data, find the facade structure (doors, windows...) and create "facade grammar" which is close to split grammar. The grammar is then used for reconstruction of parts where is a lack of information. The second utilization of the grammars is in collecting the library which can be used for city generation or to generate facades for walls with any measurement information.

Aliaga et al. [13] have presented the system for definition of grammar describing a whole building. The user first creates the model of the building and subdivides it. Then, the algorithm automatically finds repetitive patterns of the building features and constructs a representative grammar, see figure 7. Unfortunately, there is a lot of human work with initial modelling and subdividing.

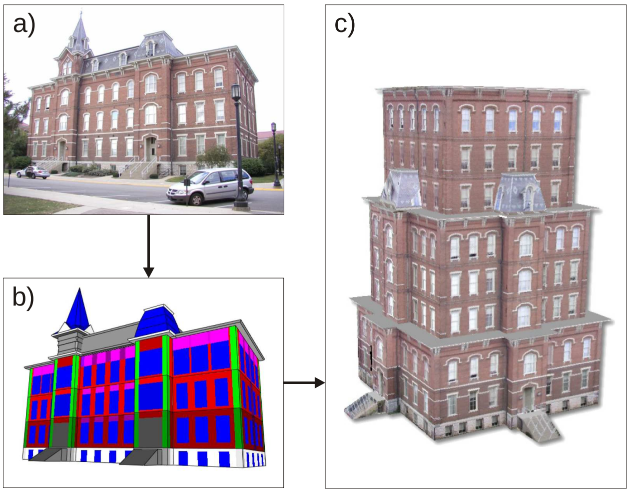

Figure 7: Aliaga et al. [13]. Input photo, subdivided building, newly generated model.

4.4 Computer Vision & Procedural Modelling

It is hard to get a complete (detailed and without artefacts) model of a building from images in 3D reconstruction. The reconstruction algorithms tend to fail in areas of occlusions, specular reflections or textures with low gradient as is flat painted wall. The algorithms considering the architectural scene structure seem to be more robust, even in areas with lack of information, they produce meaningful reconstructions [32]. In the last years, the works incorporating higher information has originated in the field of building reconstruction. The reconstructed objects are verified to accomplish grammar rules [5], [33], [34] or the grammar is used to reconstruct parts with lack of input data [6].

Vanegas et al. [5] have presented passive computer vision method for Manhattan-world building reconstruction using grammars from several calibrated aerial images. The calibrated images are segmented by a colour, separated from background and cleaned of windows using morphology. Then, the building geometry is generated based on grammar (rewriting rule), which adopt the facade orientation changes observed in the segmented photos. The input photos are then projected onto the reconstructed model. The drawbacks of this method are in limitation on buildings where all walls are oriented only at three mutually orthogonal orientations and each floor is of the same size or smaller than the floor bellow. The next problem is the necessity of observing colour changes corresponding to changes of wall orientations, so the shadows can be interpreted as wall orientation changes, and on the other hand, if building does not have lighter/darker parts it cannot be reconstructed. Finally, the model resolution is low due to input data.

The interesting approach connecting computer vision and procedural modelling was presented by Wu et al. [33]. The goal of their work was to reconstruct Chinese Ancient Pagoda from one still image. They have generated several images of pagodas using L-system and then they have used these images to train a neural network to reconstruct the pagoda from representative feature vectors. Note that this approach is limited only on symmetrical building with known style, as the pagoda is.

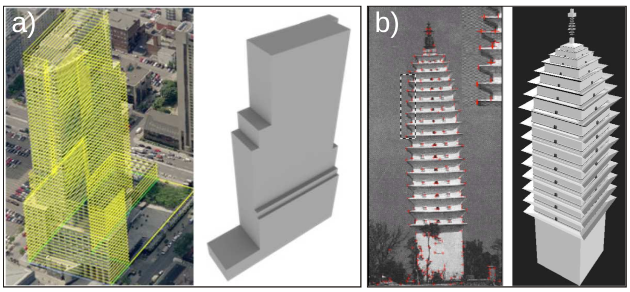

Figure 8: Two examples of connection between parametric modelling and computer vision: a) Manhattan-world building reconstruction [5], b) Chinese pagoda reconstruction [33].

The last two mentioned articles show that the architecture style determine the reconstruction methods and can help with reconstruction even if the input data set is not enough extensive. In this case, the usage of formal languages is a logical extension of reconstruction techniques to achieve full model stability and validity. Furthermore, they show that for different architectural styles (and cultures) different algorithms are necessary. If the architecture can be described, then there is a possibility to create general parameterized building reconstruction algorithm that will automatically create desired building from input data and architecture description. For this purpose it is important to find a good formal language that well describes whole building of different architectural styles and not only the “box” buildings or other buildings with special properties.

5. Conclusion

We have summarized the state-of-the-art in the procedural modelling of building architecture and we have described the possible connection to computer vision. This topic has an intersection to architecture, urbanism, computer graphics and vision, history and other research fields. The main contribution of our work is description of possible connections between procedural modelling and computer vision in this field, and the new view on the city structure in relation with time.

We have shown the promising results of inverse procedural modelling techniques that allow generation of buildings similar to original architectural style. The connection between computer vision and inverse modelling promises extraction of additional information from reconstructed objects and enable generation of rules based on this information.

Similarly computer vision algorithms based on the fact that architectural style is known have been shown. This additional information has enabled the generalization of the algorithm on similar objects, while the algorithm automation was still preserved. Also an example of how the formal rules can enrich the computer vision algorithms to be more robust has been shown.

It seems to be a closed circle that formal rules are generated by computer vision algorithms that need a formal rules to be robust and universal.

Procedural modelling of cities is heading more and more to interaction, inverse modelling, realistic look, physically based modelling and usage of fourth dimension – time.

Although the procedural modelling is nowadays heavily researched topic, we are still far from generation of realistic cities from the scales from kilometres to millimetres. The problems are mainly in grammar creation, where it is hard to find complex rules describing the system, and in the computer vision algorithms, which are not well suitable to create models plain for inverse systems.

Acknowledgements

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