Abstract

The formation of informal settlements in and around urban complexes has largely been ignored in the context of procedural city modeling. However, many cities in South Africa and globally can attest to the presence of such settlements. This paper analyses the phenomenon of informal settlements from a procedural modeling perspective. Aerial photography from two South African urban complexes, namely Johannesburg and Cape Town is used as a basis for the extraction of various features that distinguish different types of settlements. In particular, the road patterns which have formed within such settlements are analysed, and various procedural techniques proposed (including Voronoi diagrams, subdivision and L-systems) to replicate the identified features. A qualitative assessment of the procedural techniques is provided, and the most suitable combination of techniques identified for unstructured and structured settlements. In particular it is found that a combination of Voronoi diagrams and subdivision provides the closest match to unstructured informal settlements. A combination of L-systems, Voronoi diagrams and subdivision is found to produce the closest pattern to a structured informal settlement.


Keywords: Procedural modeling, city modeling, informal settlement, Voronoi, subdivision, L-systems

1 Introduction

1.1 Problem Statement

The problem addressed in this paper is the creation of feasible graphical models of informal settlements. In particular, the identification and use of algorithmic (procedural) techniques in the production of such models is addressed, with specific focus of identifying techniques that produce the closest matching features to those identified in aerial photographs of informal settlements.

1.2 Background

Modeling of modern cities has become a topic of great interest. Three-dimensional city modeling in particular refers to the construction and representation of terrain, streets, buildings, and vegetation of urban areas. However, the complexity and size of most urban cities is sufficient to make the creation of a 3D model a challenging one. In addition, there are many social issues inherent in a modern city, which affects both the appearance and evolution of areas within an urban setting.

Three-dimensional city models have applications in many areas and a broad variety of users. Four categories of application have been identified [Shiode 2001]: planning and design; infrastructure and facility services; commercial sector and marketing; and promotion and learning of information on cities. In addition to these applications, such models provide great potential as a tool for the understanding of urban structure, the mechanism of urban growth and spatial analysis. Hence, there are a large number of users of such models including central and local governments, urban and rural planners, environmental agencies, telecommunications companies, surveyors, architects and engineers.

Three-dimensional city models also have applications in entertainment and virtual reality. In such cases, the true structure and layout of the city is not as important as the visual believability of the city.
Procedural modeling, as opposed to manual modeling, is the process of creating models through the use of algorithms which encode the instructions needed for the creation of a model. Manual modeling processes require direct interaction with a user in order to physically model an object (using commercial 3D modeling packages). Procedural modeling alleviates the need for direct human interaction. The user sets parameter values for the algorithms, which in many cases is the only form of interaction a user has with the system. There are a number of benefits of procedural modeling:

- Procedural modeling provides an abstraction of the inner workings of the procedure [Cutler et al. 2002]. The meaning of the parameters and the valid ranges of those parameters are all that is required. Procedures within procedural modeling paradigms are aware of geometric requirements (including primitives and transformations).
- Procedural modeling is parameterised, which allows for an almost infinite amount of variation of a model. Parameterisation also allows for changes to a specific model without the need to change the entire scene [Marshall et al. 1980].
- Procedural modeling promotes database amplification, which is closely related to parameterisation. Database amplification takes in a small amount of data to begin with and through some operation generates a large amount of output [Apodaca and Gritz 2000].
- Procedures have the ability to replicate processes which occur in natural systems, and lead to the creation of structures which reflect the real world.

Procedural city modeling refers to the autonomous construction of three-dimensional cities, where only a small number of initial parameters need to be provided. Such systems make use of algorithms, rather than manual specification, to define road patterns and placement of structures on a terrain. The initial parameters affect the appearance of the final outcome, and often seeded random values are used in order to generate a rich and non-uniform appearance. However, finding the correct set of parameters (and corresponding values) in order to exactly model an existing city is near-impossible, and hence procedural cities are aimed at simulations, virtual reality and entertainment applications.

One particular feature of many cities in South Africa and around the globe is that of informal or spontaneous settlements. This refers to “dense settlements comprising communities housed in self constructed shelters under conditions of informal or traditional land tenure” [Hindson and McCarthy 1994].

The physical formation of such settlements in and around urban complexes has largely been ignored in the context of city modeling, as can be seen in Section 2. In addition, theories regarding the choice of location for such settlements have been provided, but very little is said about the internal road structure and layout of these settlements. This paper analyses the phenomenon of informal settlements in the context of two major South African urban complexes, namely Johannesburg (and surrounding municipalities) and Cape Town. In particular, the road patterns and layout of shacks which have formed within such settlements are analysed, and various procedural techniques proposed and implemented which model the identified phenomena.

1.3 Overview

This paper is structured as follows. Section 2.1 presents a review of work done in city modeling. Both non-procedural and procedural modeling techniques have been discussed as motivation for city modeling, as well as to highlight the absence of work related to procedural modeling of informal settlements. In addition Section 2.2 presents observations made in literature regarding the formation and structure of informal settlements. Section 3.1 analyses a number of aerial photographs of informal settlements, and motivates a number of schemes to be used for modeling settlement patterns. Implementation details, as well as a discussion regarding the success of these schemes are presented in Section 3.2 and Section 3.3 respectively. Finally a summary of findings is presented in Section 3.4.

2 Related Work

2.1 City Modeling

A number of different modeling techniques are employed in constructing three-dimensional city models. We make a distinction between models which are constructed from real world data, and procedurally generated models.

2.1.1 Non-procedural approaches

Much has been done in constructing accurate models of existing urban cities. This type of model-construction requires a large amount of input data, for example, data regarding the layout of buildings and roads, as well as elevation data corresponding to the height of buildings. Many types of input data are used for this purpose, and can be ranked in order of geometrical detail [Shioda 2001].

- **2D digital maps and orthophotographs**: This includes conventional aerial photographs, as well as data from Geographic Information Systems (GIS). This data is largely two dimensional and are incapable of providing the required detail for 3D model generation.
- **Image-based rendering**: Otherwise known as *photospatial virtual reality*, this technique models urban environments by converting panoramic photographs into navigable scenes [Dodge et al. 1998]. The drawback of this approach is that the
viewpoint is limited to the fixed location of the camera.

- **Prismatic building block models:** This method applies a combination of 2D building footprints (gained from sources such as the GIS) with height information in order to determine the size, location and orientation of buildings. Buildings are represented using primitives such as cubes, prisms and cylinders. A commonly used method for collecting height information is using laser scanner systems [Brenner and Haala 1999], which provide high density height information at a resolution of approximately one point per square meter. The 2D ground plane (provided by the GIS in the form of a topographical map or aerial photograph) is decomposed into primitives (rectangles), which are then extruded into the third dimension based on the height information.

- **Block Modeling with image-based texture mapping:** This method extends the prismatic building block models by mapping image-based facades onto the 3D primitives. The difficulties are numerous, and include acquiring facade images, as well as automatically detecting the correct placement of textures on the correct primitives. A method has been developed which is able to link digital maps in the form of real world video (recorded by a camera) to real-world positions with the aid of a GPS system [Kawasaki et al. 1999].

- **Models with architectural details and roof morphology:** This method allows for the extraction and reconstruction of 3D surface details. This method uses automated search techniques to identify and match roof geometries against templates [Brenner et al. 2001]. The best fitting geometry is chosen for the 3D surfaces.

- **Full volumetric CAD models:** This technique refers to the manual modeling of individual buildings based on physical building surveys and terrestrial photogrammetry.

The above methods all have the inherent problem that a large amount of data is required before the 3D model can be generated. Since this data is often in the form of aerial photographs, laser or video data, much filtering and interpretation must be done before the data can be used for model construction. Since all features of a city are encapsulated in this data, very little focus is placed on issues such as street pattern formation. All of the above techniques focus primarily on the modeling of buildings, and there is a distinct absence of reference to the formation of informal settlements.

### 2.1.2 Procedural approaches

Procedural city modeling techniques make use of algorithms and rules to generate street patterns, and position buildings. The key to this approach is a minimal set of input parameters. A number of tools exist which facilitate the generation of convincing city models.

The generation of street patterns is an important feature of procedural city modeling. For example, in [Parish and Muller 2001], L-systems are used to generate street patterns based on a number of global and local constraints. Initially a number of image maps are supplied which represent factors such as population density and elevation. These maps provide the underlying data for the global constraints which determine what types of streets form. Once the street patterns have formed, the areas between the roads are divided into lots on which building models (generated using L-systems) are placed.

Similarly Sun et al. [2002] make use templates (created from input maps representing, for example, elevation and population density) and rules that describe road patterns to create road networks. Four types of template are used, namely population-based templates, raster templates, radial templates and mixed templates. The population-based templates are based on Voronoi diagrams, with the edges of the Voronoi cells forming the roads. Raster and radial templates are created in a manner similar to the growth depicted by an L-system. The template starts with the placement of a single point, and production rules that grow the road (either in a radiating or raster pattern) until a boundary of the map’s bounding box is reached. Road patterns are guaranteed not to have any dead-ends, as the system will either extend the road segment to join another, or it will remove the road segment altogether.

Another technique for generating street patterns is used in [Marvie et al. 2003]. An initial non-oriented graph is used to represent streets, where the vertices of the graph represent the crossroads. Edges (representing roads) are removed and vertices displaced by small amounts to introduce variation. The remaining graph is used as a base for the generation of roads, crossroads and footprints for the extrusion of buildings.

A similar approach is used in [Greuter et al. 2003], where procedural techniques are used to create cities with grid street patterns. The city terrain is subdivided into squares that form a two-dimensional grid. Each square’s location determines what type of structure is generated within its bounds. Structures are created according to a series of pseudo-random numbers that are seeded by the position of the square within the grid. The buildings are created through a series of extrusions and texture mappings.

Buildings within a city model can also be procedurally modeled, as in [Wonka et al. 2003; Parish and Muller 2001], where modified L-systems are used to generate building features such as window and door patterns.

### 2.2 Sociological Studies

Investigation has been done regarding the reasons why informal settlements form, as well as regarding the lifestyle of the residents of such areas. This section briefly presents evidence from selected sources regarding the structure and layout of informal settlements. In particular features such as settlement location and structure, as well as housing characteristics are discussed.
A number of assertions are made in [Dwyer 1975] regarding the location of informal settlements in urban areas. One trend identified is that informal settlements typically develop on any empty land, governmental or otherwise, in and around urban complexes. This trend can be easily motivated by examples in the Ekurhuleni municipality (East of Johannesburg) where settlements have rapidly formed on mining land which recently became vacant due to the removal of mine-dumps. This trend is motivated primarily by the fact that few dwellers in informal settlements can afford the costs of commuting, and hence vacant sites close to industrial areas are especially valued. Additionally, it is often claimed that migrants first settle in centrally located settlements to be close to areas of employment, but relocate to more spacious areas on the peripherals of the city when more financial stability is achieved [Drakakis-Smith 1987].

The structure of informal settlements in urban areas is more difficult to define. Dwyer [1975] indicates that often regular grid formations occur in informal settlements, but equally often the building patterns are too chaotic to be rationalised. Manona et al. [1996] distinguishes between two types of settlement patterns based on studies of informal settlements in the Eastern Cape. Poor quality structures, and chaotic patterns tend to occur when people erect structures knowing that they will leave and build elsewhere. However, when people have clear intentions of settling, more formal patterns and higher quality structures are erected. In these cases, plots must even be requested from a local committee - resulting in neat arrangements with accessible streets. Drakakis-Smith [1987] highlights an important feature which influences many South African informal settlements - aided self-help programmes. These schemes aim to upgrade informal settlements by providing basic essential infrastructure such as water, sewerage and electricity which are provided on prepared lots. This results in the formation of regular street patterns.

Typically housing structures in squatter settlements are perceived to be cube-shaped shacks built from ad hoc materials ranging from wood, to corrugated iron. However, according to Hindson and McCarthy [1994] and Manona et al. [1996] this is not always the case. In fact, often the condition of housing in informal settlements tends to improve over time, resulting, in some cases, in mud-brick structures with corrugated iron roofs. However, temporary structures tend to be of low quality, containing only a single room, and appear to be in the majority according to Manona et al. [1996], where a third of the households studied contain only one room. In addition, the aerial photographs of informal settlements around Johannesburg and Cape Town reveal that the general structural shape of shacks is predominantly cube-shaped (see Figures 2, 3 and 4).

### 3 Identification and Evaluation of Modeling Techniques

This experimentation has a number of goals:

1. Identify a subset of visual patterns found in informal settlements from South Africa
2. Suggest and motivate the use of procedural techniques which may be able to emulate such patterns
3. Implement the identified techniques
4. Provide a qualitative evaluation of the believability of each scheme in comparison with actual photographs of informal settlements

The first two goals are discussed in Section 3.1. Issues relating to the implementation of the identified techniques are discussed in Section 3.2, with evaluations presented in Section 3.3.

#### 3.1 Design

A number of aerial photographs of informal settlements from the Johannesburg region and Cape Town have been analysed. Figures 2, 3 and 4 are aerial photographs of informal settlements near Johannesburg and Cape Town [Google Maps Beta 2005]. Figures 2 and 3 represent unstructured settlement where no external planning or improvement efforts have been made. Figure 4 however, represents a structured settlement which formed after the provision of basic infrastructure such as sewerage and electricity.

**Features** The most striking visual feature inherent in the figures are the wide, winding pathways between clusters of shacks. These pathways will henceforth be referred to as major-road patterns. These major-road patterns have been manually highlighted in white in the images for clarity. As noted in Section 2.2 a highly irregular pattern is present in both unstructured settlements (Figures 2 and 3), however where basic services are provided a very structured street pattern forms (Figure 4). More difficult to identify is what is termed minor-road patterns which represent auxiliary pathways between the major pathways. The density of shacks between major-roads is also a feature which distinguishes
structuraed and unstructured settlements, with unstructured settlements being more densely populated. Crossroads tend to be more radial in nature in unstructured settlements, while the more structured settlements exhibit perpendicular intersections. Finally, parallel roads are not visible in the unstructured settlements. Table 1 presents a summary of the perceived visual features of informal settlements based on the three aerial photographs.

The following procedural tools have been identified which have the potential of capturing the identified features of informal settlements:

- **Voronoi Diagrams**: The patterns formed by major pathways within the informal settlements in Figures 2 and 3 are highly suggestive of the regions formed by Voronoi diagrams. Given a set of reference seed-points on a plane, a Voronoi diagram partitions the plane into a number of regions, where each region contains the locus of points which are closest to each reference point [Preparata and Shamos 1985]. The result is a number of irregular polygons (see Figure 5 for an example). If the edges of these polygons are interpreted as streets, the results are similar to the irregular patterns in Figures 2 and 3.

- **Subdivision**: The seeming regularity of minor-road patterns of the informal settlements in the aerial photographs suggests the use of subdivision as a modeling tool. Subdivision is the process of increasing the resolution of a mesh by adding new vertices. The locations of these new vertices are calculated in terms of the existing mesh vertices at each stage of subdivision. An example of subdivision is presented in Figure 6, which is a plane with four levels subdivision.

- **Noise**: To introduce some randomness into the layout of the informal settlements, Perlin noise [Perlin 2002] is used to distort the regular pattern created by the subdivision process. Figure 6 uses noise to displace the vertices, giving an irregular appearance.

- **L-Systems**: As an alternative to subdivision L-systems are proposed as a scheme to model the seeming regularity of minor-road patterns. An L-system is specified by a grammar, to which productions are applied a variable number of times, resulting in a dense tree-like structure. If regular angles are chosen at branch junctions then a very regular pattern forms (see Figure 7).
\[ R = 1.456 \]
\[ \omega = F(2) \]
\[ p_1 = F(s) \rightarrow F(s)[+A(s/R)][−A(s/R)] \]
where \( F(x) \) represents a line segment of length \( x \) in the current direction. The initial value of \( s \) is 2. + and − refer to positive and negative rotation about the y-axis respectively.

Figure 8: L-system grammar

The individual use of each of the above techniques are not sufficient to model convincing informal settlements. Thus combinations of the above tools are created based on observations made from the aerial photographs. Voronoi diagrams are chosen as the major street structure, with the initial choice of seed points differentiating between structured and unstructured patterns. The more random the choice of these points, the more irregular the resulting polygons. Within each Voronoi region, either subdivision or L-systems are used to produce grid-like patterns. Regular grids are avoided by displacing vertices using noise. Table 2 presents a summary of the experiments conducted.

3.2 Implementation

The procedural tools used for these experiments are implemented in the following manner:

- **Voronoi Diagrams**: An initial set of points (regular or random) are generated on the \( x-z \) plane as reference seed points for the Voronoi diagrams. The corresponding Voronoi diagram is generated using the \texttt{QVORONOI} application of the \texttt{QHull} package [Barber et al. 1995].

- **Subdivision**: \( \sqrt{2} \)-subdivision, presented in [Li et al. 2004], is implemented for these experiments. The mesh to be subdivided can be of arbitrary topology and consist of either triangles or quadrilaterals. The scheme has been altered to maintain the area of the mesh passed to it, by not displacing the original vertices. Another modification to the subdivision scheme is the addition of noise to displace the \( x \)– and \( z \)–coordinates of each newly created vertex.

- **L-Systems**: The L-system implemented is described in [Prusinkiewicz and Lindenmayer 1990], with the grammar presented in Figure 8. This produces a regular placement pattern, as shown in Figure 7. A regular pattern is produced by setting the angle of rotation to 90 degrees. An irregular pattern is produced by randomising this angle within a restricted range.

The generation of procedural informal settlements is achieved as follows. The initial set of reference points for the Voronoi diagram is generated (random or regular), and the corresponding set of Voronoi polygons is produced. Where subdivision is used for minor-road patterns, each polygon is treated as an individual mesh which is subdivided a number of times (relative to the
area of the polygon). Each resulting vertex in the mesh is used as a placement location for a shack in the settlement. Where L-systems are used as minor-road patterns, the structure is grown within the polygon by applying production rules a number of times. Any vertices falling outside the polygon are discarded. The endpoints of the L-system are used as placement locations for the shacks. L-systems are also used to generate major-road patterns by producing a regular set of reference points for the Voronoi diagram.

In order to achieve major-road patterns (in the form of gaps between shacks) in the settlement scheme, any shack which falls too close to the edges of the Voronoi polygons are discarded.

The shape and texturing of shacks is of minor importance in these experiments. Since shacks are predominantly cube-shaped, each shack in the model is represented as a untextured cube. Images are rendered using OpenGL.

### 3.3 Results

#### Experiment A

Figure 9 presents an unstructured informal settlement using 80 random Voronoi seed-points, with each Voronoi region adaptively subdivided according to the area of the region. Each shack location is displaced according to a noise function. Additionally the orientations of the shacks are adjusted so that at least one face of the shack is aligned with the closest Voronoi boundary.

A highly irregular major-road pattern emerges from this model, with unpredictable crossroads and junctions. The major-road pattern is clearly visible and is greatly enhanced by the alignment of the shack faces with the closest road. Minor-road patterns are more difficult to identify. The distribution of the shacks is uniformly dense. There is no pattern to the structure of the roads, with parallel roads scarcely occurring. It is possible however to identify a number of radial road patterns.

#### Experiment B

Figure 10 presents a combination of Voronoi regions (from 80 random Voronoi seed-points) and L-systems within these regions. In some areas there are emerging major-road patterns, but generally the spaces between clusters of shacks are unrealistically large. This can be explained by the nature of the grammar used for the L-system, which tends to leave large gaps between child branches. Barring the large gaps between regions, the density of shacks is largely uniform. No minor-road patterns can be identified within the regions, and the shack orientations are highly irregular. The criticism of this model is the large number of gaps which form between regions, which is unrealistic in terms of the aerial photographs provided in Section 3.1.

#### Experiment C

Figure 11 presents a more structured settlement than the previous two experiments. A Voronoi diagram is used with a smaller number of regions than in Experiment A and B (40 seed-points) and shack locations are not displaced during subdivision. However, the orientation of shacks is still modified to face the nearest roads. Once again major-road patterns emerge very clearly, but in this case minor-road patterns are more distinguishable than in previous experiments. The shack placement is very dense, and very uniform, giving the impression of structure. The criticism of this model is that there are regions of shacks which are too regularly distributed, displaying placement patterns which cannot be seen in the aerial photographs of informal settlements provided.

#### Experiment D

Figure 12 presents another attempt at a more structured settlement. A randomised Voronoi diagram (with 40 random Voronoi seed-points) is used, and a non-randomised L-system (branching angles of 90 degrees) is used within the Voronoi regions. The problem with this model is the sparseness of shack placement. This is a result of the L-system grammar, which grows
Figure 10: **Experiment B:** Random Voronoi seed, Voronoi regions contain L-systems (random angles)

Figure 11: **Experiment C:** Random Voronoi seed, Voronoi regions subdivided without noise

Figure 12: **Experiment D:** Random Voronoi seed, Voronoi regions contain L-systems (regular angles)

Figure 13: **Experiment E:** Regular Voronoi seeds, Voronoi regions subdivided with noise

too rapidly beyond the bounds of the Voronoi regions. The sparseness of shacks is not conducive to the formation of clear major-road patterns. The distribution of shacks within the regions is largely regular, often forming a clear grid pattern. In terms of the provided aerial photographs this model does not appear to be realistic of unstructured settlements, but such patterns could occur in more structured settlements where lots have been allocated.

**Experiment E** Figure 13 presents the results of a Voronoi scheme based on regularly distributed seed-points. This results in a major-road structure which has a typical grid pattern. Irregularity is still maintained by employing noise in the subdivision of the Voronoi regions. Minor-road patterns do not emerge clearly. The density of shacks is not uniform, even though the size of the Voronoi regions are uniform. This is attributed to the noise applied to the vertices during the subdivision process. The criticism of this model is the overarching uniformity of the major-road patterns, which is uncharacteristic of road patterns shown in the aerial photographs, which are more unpredictable.

**Experiment F** Finally, Figure 14 presents a hybrid of procedural methods. The regular L-system is used to generate the seed points for the Voronoi diagram, and the resulting Voronoi regions are subdivided with noise displacements. This figure provides a good example of a structured informal settlement. Major-road patterns such as parallel roads and perpendicular cross-roads are clearly visible. However, the major-road pattern is not totally regular, and there exist a number of diagonal roads, and radial intersections. The density of the shacks is also uniform in all the regions, and their orientations are convincingly regular. The main contributor of irregularity to this model is the use of noise, which has sufficiently perturbed the placement of shacks to reduce the overall impression of structure. The only criticism of the results produced by this model is the perceived symmetry, which is an artefact of the L-system which was used to create the Voronoi seed-points. In our opin-
3.4 Summary and Conclusions

Voronoi diagrams, L-systems and subdivision have all been tested as possible procedural modeling techniques for informal settlements. Qualitative conclusions are drawn regarding the best model for unstructured and structured settlement patterns. These conclusions are based on the features extracted from the aerial photographs in Section 3.1. Table 3 presents a summary of the qualitative comparisons made regarding the features identified in each experiment.

The conclusions according to Table 3 are as follows:

- Experiment A produces the most convincing unstructured pattern
- Experiment F produces the most convincing structured pattern
- Voronoi diagrams produce convincing major-road patterns in all cases
- Minor-road patterns are not readily identifiable when subdivision (with noise) is used. This is attributed to the large amount of variability caused by noise.
- The formation of perpendicular and radial crossroads is successfully achieved using various combinations of techniques.
- Generally, subdivision works better than the chosen L-system for populating the Voronoi regions

It is important to note that the conclusions presented here regarding the closest matching settlement pattern are qualitative in nature. Further work must be undertaken to identify quantitative measurements which can be used to differentiate between structured and unstructured settlements. Furthermore, a larger base of aerial photography will be beneficial in classifying various types of informal settlements.

4 Conclusion

This paper provides an overview of various types of city modeling techniques, both procedural and non-procedural. A novel problem, in the form of informal settlements, has been identified within the context of urban city modeling. A study of the structures of informal settlements is provided, and a number of aerial photographs are used to identify features of informal settlements including road patterns and density. These features are chosen with the aim of aiding in the choice of procedural techniques for the modeling of informal settlements. A number of procedural techniques are identified and tested for appropriateness against the original aerial photographs.

A number of novel contributions are made. Firstly, the inclusion of informal settlements into the context of city modeling is an unexplored area. Secondly, novel combinations of procedural techniques (including Voronoi diagrams, subdivision, and L-systems) are evaluated.

Further work includes adding a time dimension to the procedural techniques in order to simulate the growth of such settlements. Additionally, other combinations of procedural techniques can be tested (for example fractals), with the inclusion of global parameters such as water availability and land topography. A more detailed and theoretically grounded set of features should be extracted by analysing a larger set of aerial photography and settlement literature.

References


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Table 3: Summary of findings

Internet GIS for urban planning. In Virtual Reality and Geographical Information Systems Workshop.


