RECONSTRUCTION OF KYOTO OF THE EDO ERA BASED ON ARTS AND HISTORICAL DOCUMENTS: 3D URBAN MODEL BASED ON HISTORICAL GIS DATA

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Abstract   This paper explores a method for creating large-scale urban 3D models using Historical GIS data. The method is capable of automatically generating realistic VR models based on GIS data at a low cost. 3D models of houses are created from polygon data, fences from line data, and pedestrians and trees from point data. The method is applied to the Virtual Kyoto Project in which the landscape of the whole city of Kyoto of the early Edo era (ca 17C) is reconstructed.

Keywords: GIS, Automatic Generation, 3D urban model, Kyoto

INTRODUCTION

Digital urban 3D models are currently created for use in fields such as landscape planning, urban environmental planning, car navigation systems, and the real estate industry. Demand for urban 3D models is also growing in academic research and in the presentation of research results in the humanities and social sciences. However, generating such models over large areas requires a substantial amount of money and time. Consequently, urban 3D models are usually only created and used in highly profitable practical fields.

Since the Geographic Information System (GIS) revolution that began in the latter half of the 1980s, the collection of 2D data has improved as the

development of new measurement techniques and the availability of high-resolution satellite data have led to the extensive accumulation of a range of geographical information.[1] Technical innovations associated with the IT revolution has made it possible for individuals to easily access a more familiar virtual space. For example, Second Life provides a 3D virtual world,[2] and Google Earth provides the real world in a virtual 3D space.[3] Both of these applications use a standard Internet connection to deliver data from the server to the client online, thus achieving a virtual space in which the user interacts with the virtual environment.

This paper establishes a method for automatically generating urban 3D models using existing GIS data to meet the demand for such models at low cost. There has been a great deal of research concerning the development of a method for the automatic generation of houses from building footprint polygons in GIS data.[4] This study provides a comprehensive discussion of the automatic generation of 3D features, including the creation from geometry types other than polygons (lines and points). As a specific example of an application of our method, an urban 3D model of the entire City Kyoto of the early Edo era (*ca* seventeenth century) is generated based on GIS data for that era, which were prepared by the 'Historical Geographical Information Research' unit for Ritsumeikan University's Global COE Programme, titled 'Digital Humanities Center for Japanese Arts and Cultures' (funded by the Ministry of Education, Culture, Sports, Science and Technology, Fiscal 2007–2011).[5]

The Global COE programme deals with digital archiving of arts, craftwork, historical documents, and performing arts, and experimenting with the use of information technology for humanities research. Alongside its main research agenda, the programme devotes a substantial share of effort in disseminating its findings to wider public, and our attempt to create an 3D urban model of the whole city of Kyoto during the Edo era is a key part of this outreach. Such work has been crucial for attracting and maintaining the funding for the programme. The 3D urban model will be distributed on the Web to disseminate Kyoto's traditional culture all over the world by placing tangible and intangible cultural heritage within the 3D model. The 3D urban model acts as an intuitive interface to the database of digitally archived materials. For this purpose, we created an urban 3D model that can be delivered over a standard Internet connection.

The remainder of this paper is organised as follows. The second section describes historical GIS data sources that our 3D urban model draws upon. The third provides a general outline of the program used to automatically generate 3D models from the 2D GIS geometries, the fourth describes the generation of 3D models from polygons, lines, and points. The final section summarises the current knowledge pertaining to the effective generation of urban 3D models, as obtained via the experience of automatically generating an urban 3D model of Edo-era Kyoto.

HISTORICAL GIS DATA SOURCES

The accumulation of GIS data is currently at a considerably advanced stage: satellite images or digital elevation models are offered often free of charge and can be readily used for large-scale 3D urban models. However, accurate sources of information that are regarded as 'data' are not usually available for historical eras such as the Edo era. The creation of the 3D urban model in this paper is based on arts and historical documents of that period.

The primary data source is a pre-modern map from the early Edo era, the *Kanei-go-manji-mae-rakuchu-ezu* (Kyoto University Library; hereafter referred to as the *rakuchu-ezu*), *ca*. 1642. The high level of detail of this map allows near-exact identification of samurai residences, temples, shrines, and palace grounds. The map was scanned, digitised and rectified for any distortions to match with modern maps.[6] Our basic approach in creating the urban 3D model of Edo-era Kyoto is to automatically generate housing models for residential areas, fence models for plot boundaries of palaces and manors, and trees in homestead woodlands and mountain woodlands based on the GIS version of the *rakuchu-ezu* (Figure 1).

Information corresponding to the lateral view must be added to the 2D plan in order to generate historical 3D model. The *shihonkinjichakushoku-rakuchu-rakugai-zu-rokkyokubyoubu* (Hayashibara Museum of Art; hereafter referred to as the *rakuchu-rakugai-zu*), also created in the early Edo era, was used as the source of this information. The *rakuchu-rakugai-zu* is a pair of artworks on folding screens, drawn as if looking from a distant aspect of the city, depicting various buildings and the way of life of the townspeople (see the image at Hayashibara Museum of Art Website[7]). The types of houses in the *rakuchu-rakugai-zu* were counted to find the frequency of each type of house. Images of buildings and pedestrians were traced to create the textures that will be pasted on to the 3D models. As the data were sourced from works of art, they cannot be considered as objective data on the streets of the Edo era; however, as there were no objective data to begin with, our 3D model is created to match the *rakuchu-rakugai-zu*. If more reliable data or hypothesis becomes available, it would be easy to re-generate a 3D model covering the whole city based on the new data using the current method. This is an advantage of generating 3D models automatically. We have, however, used the best contextual material currently available.

3D MODEL AUTO-GENERATION PROGRAM

For the purpose of developing the '3D model auto-generation program' that automatically generates urban 3D models from 2D GIS data, we used Excel, Microsoft's spreadsheet software, and VBA, its associated macro language. The well-developed program can be used on any PC with Excel installed.
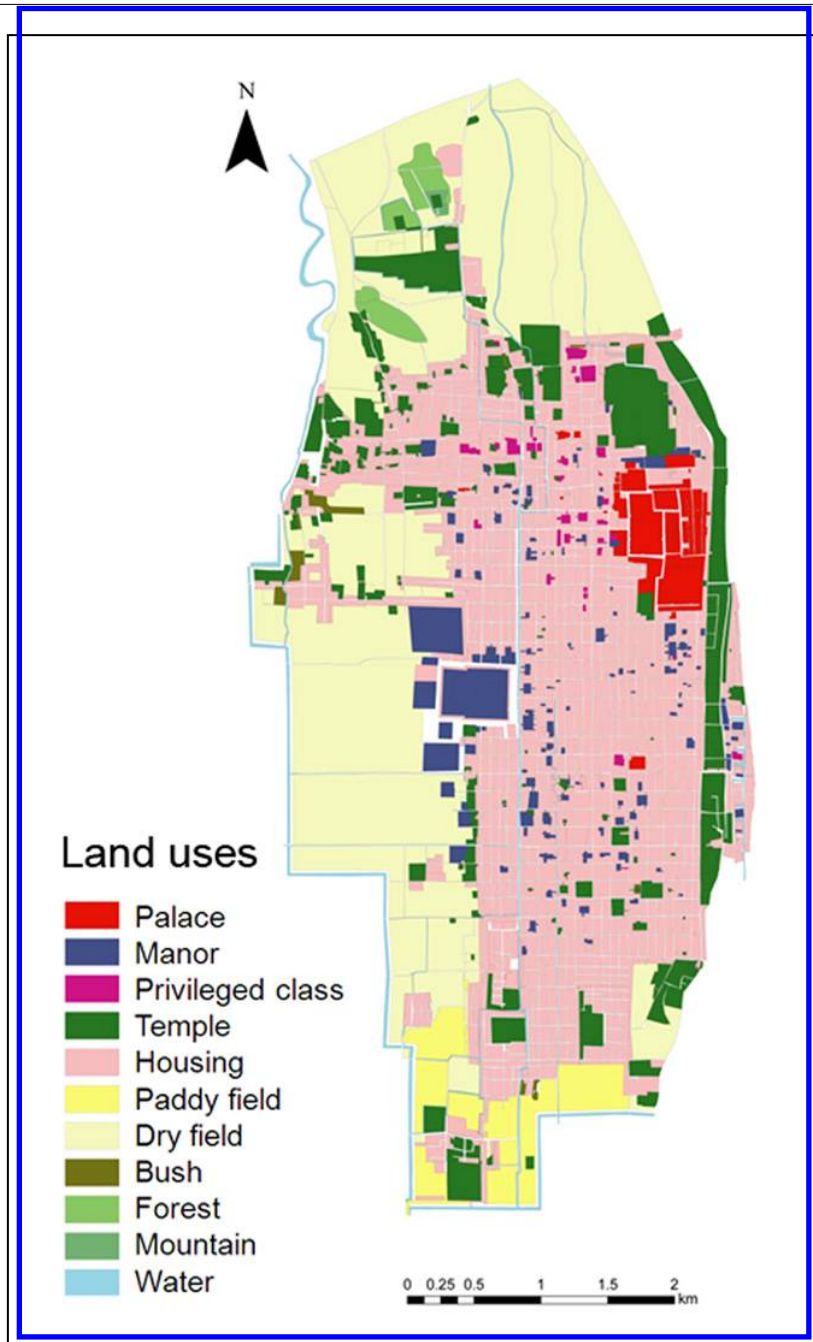
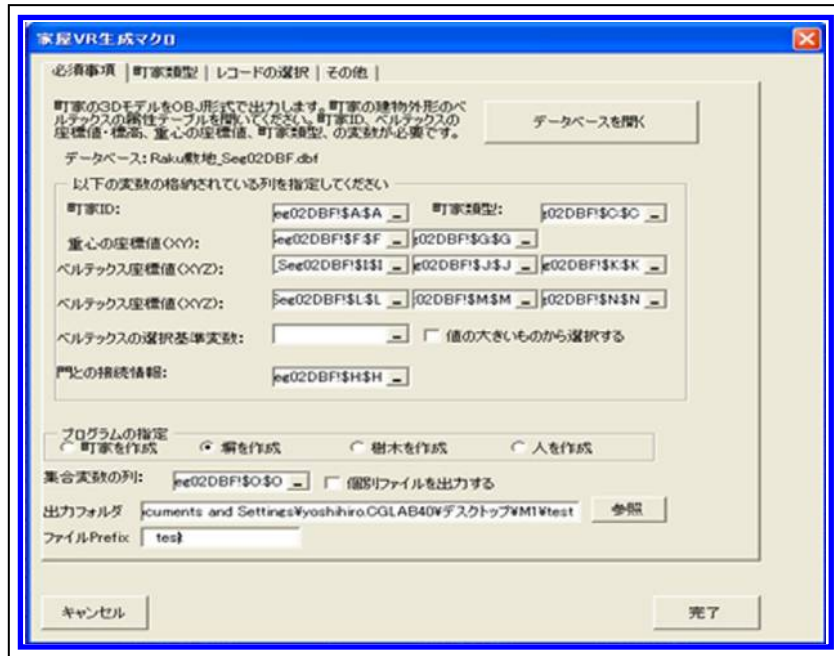**Figure 1.** Digitized *Rakuchu-ezu* (*ca* 1642, Kyoto University Library).

Figure 2. User Form.

Spreadsheet software was adopted as the platform for the program to run on because it is well suited to describe 'parametric 3D models'. In general, 3D models are made up of surfaces defined by a set of nodes in three dimensions. In parametric 3D models, the coordinates of these nodes are represented by mathematical expressions using parameters rather than explicit values. Spreadsheets, in which cell values are referred to calculate the required value, are exceptionally well suited to describing such nodes.

The 3D model auto-generation program employs a User Form (Figure 2) that allows users to specify where to look for the values of the coordinates that make up the 2D geometry (plot shape, plot boundaries, and trees) in the GIS data. For each record in GIS, the program substitutes the coordinate values into one of the multiple spreadsheets that describe a parametric 3D model in accordance with the GIS attribute data (e.g. type of house). Similarly, the appropriate textures are selected from the provided texture libraries according to the attribute data and pasted onto the surfaces of the generated 3D model. The whole street scenes are automatically generated by repeating this sequence of steps over the entire city.

Our program can use all database file formats that can be read by Excel as GIS attribute data. The parametric 3D models described on each sheet conform to the

Wavefront OBJ file format, meaning that the calculation results after coordinate substitution can be output as OBJ files. The OBJ file format is a text file for describing three-dimensional shapes, and has become widespread because of its simple structure[8]. Furthermore, OBJ files only describe geometric information and information on texture is recorded separately in MTL files. The 3D model is rendered by inputting these OBJ files, MTL files and texture libraries (collections of image data used to provide textures and referred to by the MTL files) into an appropriate visualisation application. We have used UrbanViewer™ (CAD Center Co.) for rendering which has capability to disseminate rendered CG images over the internet.

AUTOMATIC GENERATION OF 3D MODELS

There are three types of geometries in GIS spatial data: data that can be represented by points, such as people and trees; data that can be represented by lines, such as railroads and fences; and data that can be represented by polygons, such as houses.[9] These geometrical data types represent a range of real-life features. In this paper, we first create 3D models of *kyomachiya* (Kyoto's traditional merchants' and artisans' houses) as an example of transforming polygons into 3D objects. A 3D model of a fence is then created as an example of transforming lines into 3D objects. Finally, trees and people are created as an example of making 3D objects from points.

1.1 Automatic Generation of Houses from Polygon Data

1.1.1 Parametric 3D Model of Kyomachiya

In the streets of historic Kyoto, the *kyomachiya* – the dwellings of merchants and artisans – occupied the majority of the area.[10] Some of those survive today, and the '*Kyomachiya* Database' (run by Ritsumeikan University, Kyoto City and *Kyomachiya* Reconstruction Research Association) provides the attribute data in GIS data format, including the distribution of around 24,000 *kyomachiya* buildings in seven types of *kyomachiya* houses.[11] Parametric 3D models of these seven types of houses were created from existing *kyomachiya* (Figure 3).

In reality, we do not know the types of individual houses in Edo-era Kyoto. Even the individual plots in the Edo-era street blocks are unknown. Therefore, GIS was used to integrate the plots in the *Kyoto-chiseki-zu* (Kyoto Cadastral Map), published in the first year of the Taisho era, onto the street blocks in the *rakuchu-ezu* to create the housing plots of the Edo era. The composition of the house types was calculated from the aforementioned *rakuchu-rakugai-zu* (Table 1),[12] and the house types were allocated at random based on these frequencies.

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(a) Full Two-story   (b) Mezzanine   (c) Three-story   (d) Single-story

(e) Residential   (f) Fenced Residential   (g) Billboard

Figure 3. Parametric 3D models of the seven types of *kyomachiya*.

Table 1. Proportion of *kyomachiya* types in the *rakuchu-rakugai-zu*.

Kyomachiya Type	Number of *Kyomachiyas*	Percentage %
Single-story	86	36.4
Mezzanine (small)	66	28.0
Mezzanine (large)	84	35.6
Total	236	100.0

1.1.2 Specifications of the Kyomachiya *Auto-Generation Program*

Kyomachiya are characterized by their narrow width and long depth. The front of the building stretches right across the entire plot to the very edge of the adjacent houses. No space is left between the houses and the road, and the houses are built facing directly onto the street. Therefore, the first important point in creating a *kyomachiya* model from a parametric 3D model is where to put the front door. To do this, the distances between the road and the nodes constituting a plot are measured in GIS, and our program selects the two nodes with the smallest distances (nodes (1) and (2) in Figure 4).

Once the front door has been determined, the house's *kyomachiya* ID, *kyomachiya* type, center coordinates, and coordinate values for the first and second nodes are substituted in the spreadsheet that describes the parametric 3D model. If the *kyomachiya* type is unknown (which is usually the case), it is selected at random from the seven types of *kyomachiya*. Then the depth, height, and other nodes of a house are calculated, and a *kyomachiya* model is created.
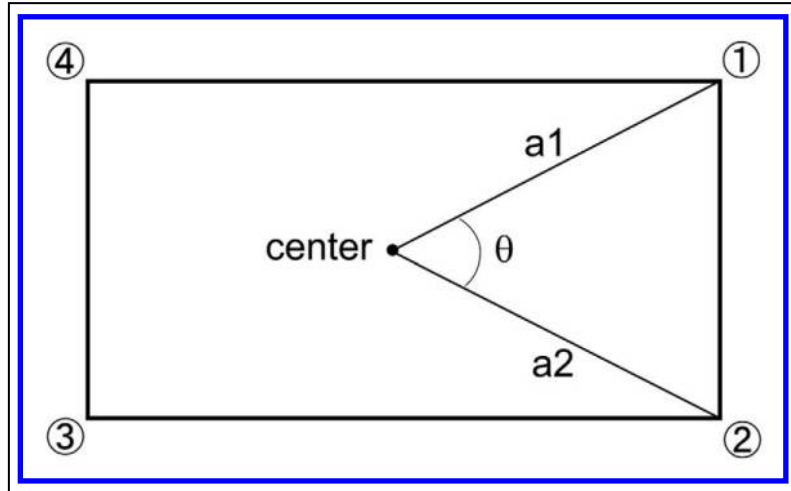
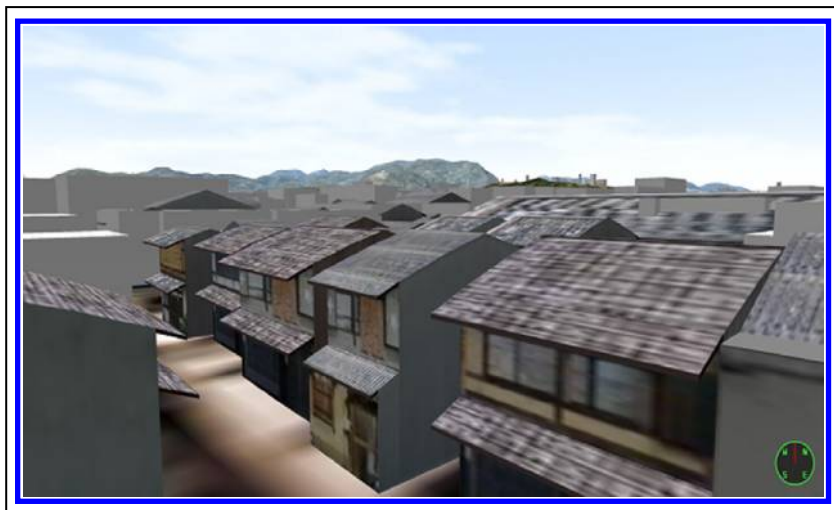**Figure 4.** Determining the position of the front door.

Figure 5. 3D Model of *kyomachiya*.

At the same time, the texture is also chosen using the MTL file that sorts the images from the provided textures. This process is repeated for all the housing plots in the database. Figure 5 shows a part of the model created covering the entire town area of present-day Kyoto.
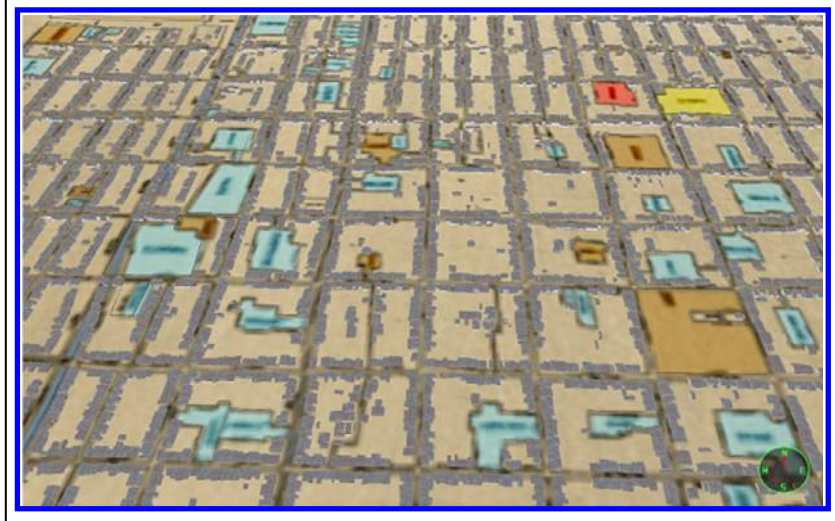
Figure 6. The streets of Edo-era Kyoto seen from above.

1.2 Automatic Generation of Storehouses

1.2.1 Structures within a Plot

In the process of the automatic generation of *kyomachiya* described thus far, buildings facing onto the streets have been created, but open spaces have been left in the middle of the street blocks (Figure 6). However, the *rakuchu-rakugai-zu* shows storehouses, trees, or wells within the plots. Therefore, we first considered automatically generating storehouses at the back of *kyomachiya*. Given the absence of GIS data related to storehouses, they were positioned automatically within the grounds of the *kyomachiya* using an appropriate algorithm.

1.2.2 Specifications of the Storehouse Model Auto-Generation Program

Given that a tax was imposed during the Edo era according to the width of the front of the house, it can be presumed that the larger the front door, the more affluent the household. Accordingly, as a criterion for the automatic generation of storehouses within plots, it was decided only to create a storehouse for townhouses that had a frontage of at least a certain size (a front door of 3 *ken*, approximately 5.45 m) and a depth at least twice the frontage. Figure 7 shows the appearance of a storehouse displayed together with a *kyomachiya*.

Figure 7. Example of a model of storehouse attached to a *Kyomachiya*; seen from the front (left) and from the back (right).
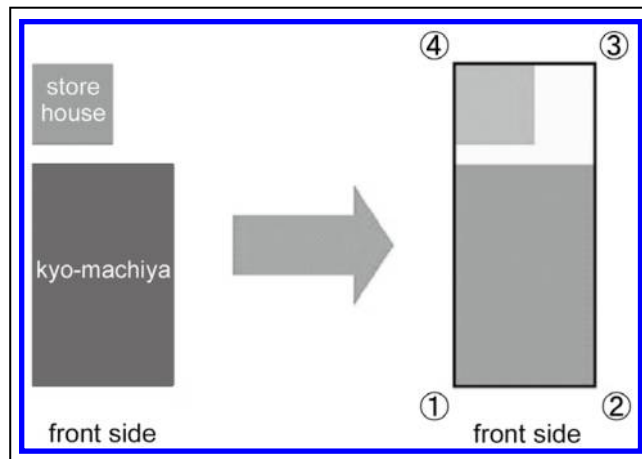

Figure 8. Method used to determine the hypothetical plots.

1.2.3 Conflict-Avoidance Algorithm

If storehouses, which are not in the original GIS data, are automatically generated and positioned according to the rule above, then neighbouring premises may conflict, a situation that must be avoided. Since storehouses are created together with *kyomachiya*, rectangular hypothetical plots that cover both the *kyomachiya* and the storehouse are generated (Figure 8), and hypothetical plots can be used to detect conflicts. Figure 9 shows a street block when only *kyomachiya* are created and when *kyomachiya* and storehouses are created employing the conflict-avoidance algorithm.
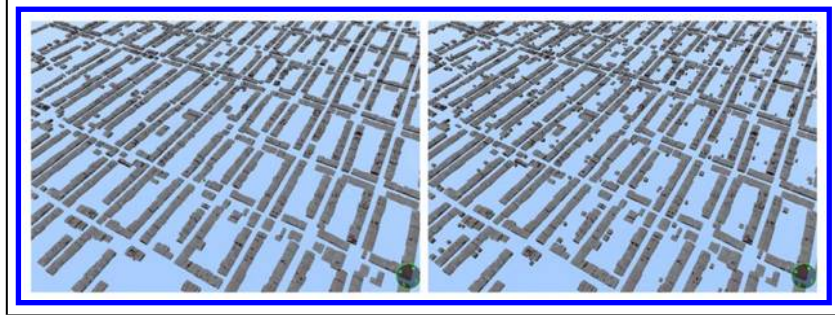
Figure 9. Streets with *kyomachiya* and storehouses; with only *kyomachiya*s created (left), and with storehouses added (right).

Table 2. Numbers of *kyomachiya* and storehouses in *rakuchu-rakugai-zu* and our model.

	Rakuchu-Rakugai-Zu	Our Model	
		Without Conflict-Avoidance	With Conflict-Avoidance
a) Number of *Kyomachiyas*	236	30,052	30,052
b) Number of Storehouses	33	16,664	2,824
Ratio (a/b)	14.0%	55.4%	9.4%

As a rough indicator of the accuracy of the conflict-avoidance algorithm, we used the number of storehouses depicted in the *rakuchu-rakugai-zu*. Table 2 shows the proportions of storehouses to *kyomachiya* in *rakuchu-rakugai-zu* and in our model with and without conflict-avoidance algorithm. While automatic generation based on the aforementioned rule alone over-generates storehouses, the use of the conflict-avoidance algorithm results in a placement of storehouses that more closely resembles that of the *rakuchu-rakugai-zu*.

1.3 Automatic Generation of Fences from Line Data

1.3.1 Specifications of the Fence Auto-Generation Program

In creating the streetscape, it is necessary to model the structures facing the roads. Since the frontage of the *kyomachiya* face directly onto the streets, it is essential to model the houses; however, in the case of *bukeyashiki* (samurai residences), a fence faces the street. Therefore, we considered automatic generation of the fences of the *bukeyashiki*.
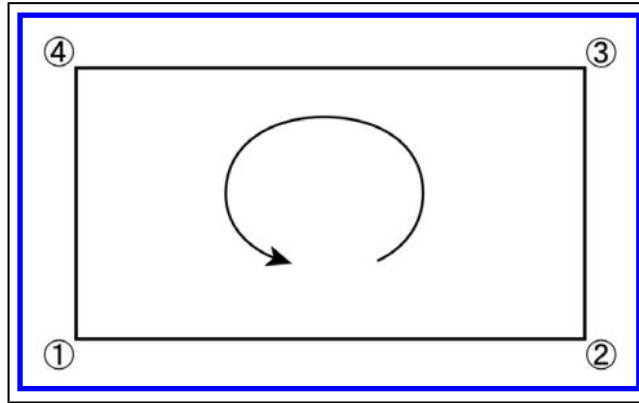
Figure 10. Method of creating a fence.

The fence auto-generation program requires the following input information: the coordinates of the nodes that describe the geometry of the plot, the type of fence, and whether a side of the plot has a gate or an entrance. First, the coordinates for two consecutive nodes are taken to represent the start (node (1)) and end (node (2)) points, as shown in Figure 10. Nodes (3) and (4) are then created by adding the fence height to the z coordinate. The created nodes are then connected in the order of (1), (2), (4), (3) to construct the fence. Similarly, the nodes are connected in the order of (2), (1), (3), (4) to generate the fence on the inner side. This process, followed to complete one section of fence, is then repeated to complete the fence that encloses the plot on which the *bukeyashiki* stands.

When the texture is pasted, more than just a single image is pasted: the length of the side is calculated and divided by the standard length of the texture. If the result is a decimal, it is rounded up to give the number of images to be pasted. This approach avoids significant distortion of image due to excessive enlargement. If a side contains a gate, then nodes (1) and (6), provided as input data, are taken to be the ends of the fence, and new nodes (2), (5), (10), (9) are created to define a gate of the prescribed width (here, a width of 1 *jo* (= 3.03m) was used) from the centre point, as shown in Figure 11. These nodes are used to split the fence, thereby defining the gate region (represented by nodes (2), (5), (10), (9)). Furthermore, nodes (4) and (7) are defined such that the gate section is taller than the fence; the surfaces enclosed by nodes (1), (2), (4), (3) and by (5), (6), (8), (7) are connected and created. For the rest of the side, fence textures are pasted in the same way as described previously.

In this way, a gate and a fence of a prescribed size can be created, regardless of the fence length. Since this program uses all node coordinates that describe
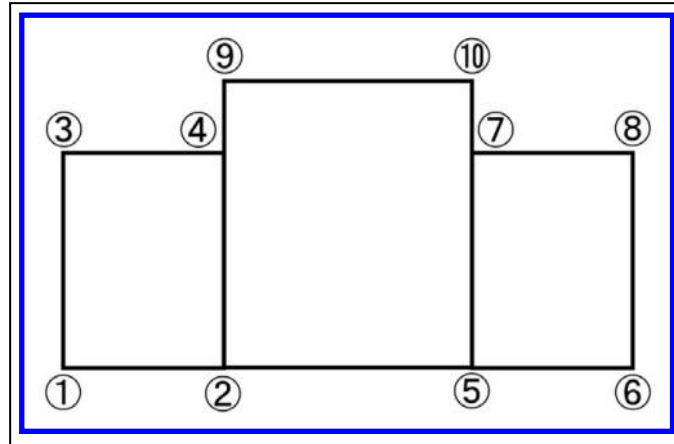
Figure 11. Method of creating a fence containing a gate.

Figure 12. Fence model.

the geometry of a plot fences with complex shapes with a mixture of acute and obtuse angles can be generated automatically (Figure 12).

An urban 3D model (Figure 13) was created using the fence auto-generation program described above for the samurai areas, nobility areas, and temple and shrine areas in *rakuchu-ezu*, and by applying the house auto-generation program

Figure 13. *Kyomachiya* and a fence of a *bukeyashiki*.

on the urban areas. In addition, images of *kyomachiya* depicted in the *sanjo-aburanokojicho-higashigawa-nishigawa-machinami-emaki* (Kyoto Prefectural Library and Archives) of the late Edo which has a realistic representation of buildings were used for the textures of *kyomachiya*.

1.4 Automatic Generation of People and Trees from Point Data

1.4.1 Creation of Point Data

So far we have described the automatic generation of buildings, but this only achieves inactive, lifeless, streets. Therefore, we attempted the automatic generation of people and trees from GIS point data to breathe life into the historical streets. In adding details to urban 3D models, if many details are to be added, the key issue is to create realistic objects without making file size too big. Billboards models were used for the people and trees for this reason. Naturally, no GIS data exist for people or trees; consequently, the probability distribution was assumed spatially on the GIS, and billboards were placed at randomly chosen points to create people and trees.

1.4.2 Specifications of the People Auto-Generation Program

People were represented by cutting out and processing images of people from the *rakuchu-rakugai-zu* and *sanjo-aburanokojicho-higashigawa-nishigawa-*

Figure 14. Recreated Shijo-dori in the Edo era.

machinami-emaki to create the textures, and by pasting them onto billboards. The textures also have an α channel added to specify the parts of the image that must be transparent. Moreover, in the pursuit of realism, the billboards for pedestrians were angled by randomly rotating them a certain range off the centerline of the street. By automatically generating and constructing people in Shijo-dori, we recreated the street scene shown in Figure 14.

1.4.3 Specifications of the Tree Auto-Generation Program

Tree billboards were created such that they cross perpendicularly at the given data point (Figure 15). An α channel was added to the used textures, as with the people textures, to ensure that only the tree parts of the texture are displayed. Furthermore, by using random numbers for the scale and rotation angle of the billboards, sufficient variation avoiding any impression of redundancy is obtained with just 10 tree texture variations.[13]

CONCLUSION

This research led to the development of a method and application program to automatically generate and position 3D models of generic geographical features on a large scale; houses and storehouses from GIS polygon data of building plots;
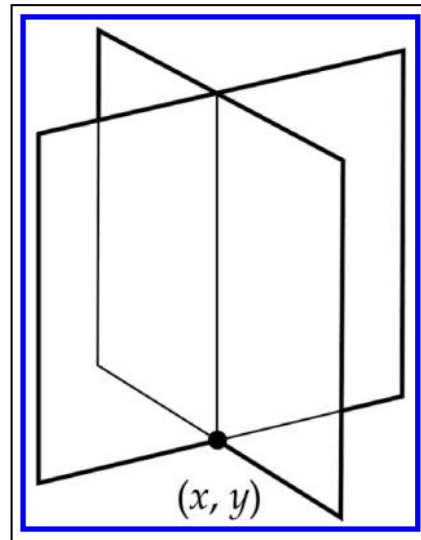
Figure 15. Method of creating trees (billboards).

fences from GIS line data of plot boundaries; and models of people and trees from GIS point data created hypothetically. This program can be used to generate urban 3D models automatically from 2D data that are either hypothetical or reconstructed from fact. In particular, this paper described the employment of this method and application program to the reconstruction of Edo-era Kyoto streetscapes, thereby confirming the effectiveness of the method. We believe that we have basically achieved this aim (Figure 16).

However, our method is only applicable to generic geographical features, and for buildings having unique features, it is necessary to create them manually. To add some more realism in our model, landmarks such as the Keep of Nijo Castle and the Five-Story Pagoda of Toji Temple, are created based on blueprints.[14] These models are integrated with the automatically generated data by appending the data into the OBJ file (Figure 17).

The greatest advantage of this method when creating historical urban 3D models is its flexibility: the 3D model can be created from factual data, where such data exist, and a certain amount of hypothetical data can be used to construct imaginary models in cases where no factual data exist. A complete collection of historical data, covering the entire area of interest, will rarely be obtainable. Accordingly, hypotheses are established from qualitative or quantitative data that can be partially obtained based on historical materials such as pictures. The proposed method can be used to incorporate these hypotheses via simulations. For example, if the density distribution of trees or the pictorial
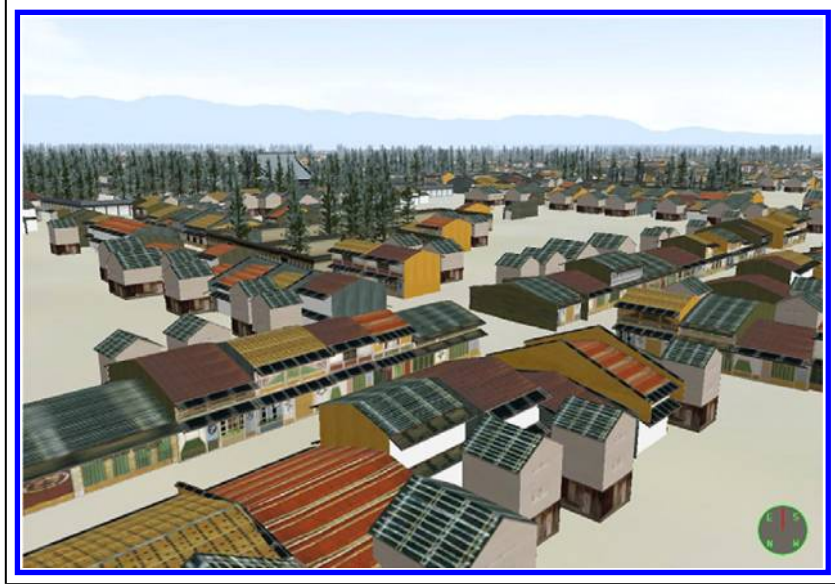
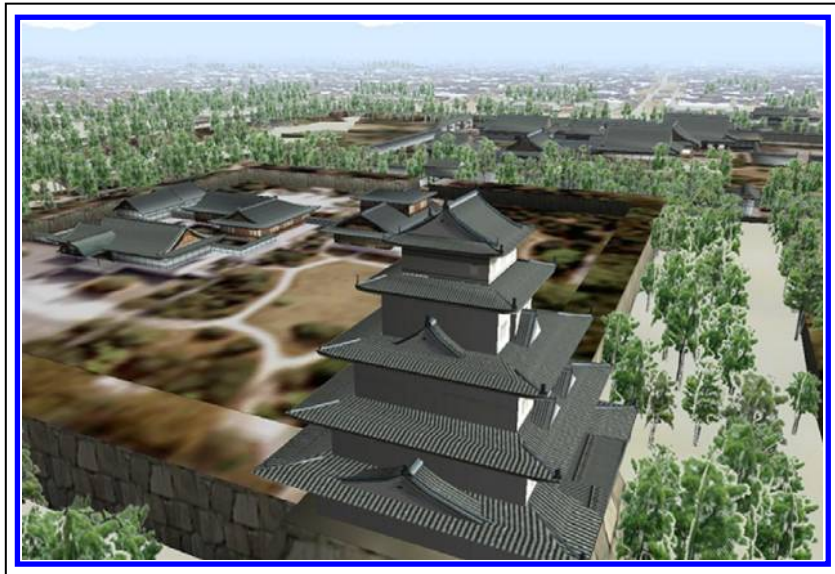**Figure 16.** Reconstructed streetscape in *Rakuchu*.

Figure 17. Reconstructed street scene of *Rakuchu* and Nijo Castle Keep.

materials were changed to form a different hypothesis, visualisation could be achieved in the same way, simply by altering the parameters and re-pasting the textures, thereby making it easy to compare various hypotheses.

Although our concrete example was based on GIS data specially prepared for the Virtual Kyoto Project, the accumulation of historical GIS data is progressing worldwide and the method proposed here is a practical, cost-efficient way of creating urban 3D models. The proposed method has the potential to be widely employed, regardless of the era or location of interest.

END NOTES

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