Y. Ikeda, C. M. Herr, D. Holzer, S. Kaijima, M. J. Kim. M, A, Schnabel (eds.), *Emerging Experience in Past, Present and Future of Digital Architecture, Proceedings of the 20th International Conference of the Association for Computer-Aided Architectural Design Research in Asia CAADRIA* 2015, 241–250. © 2015, The Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong

DEVELOPMENT OF A KINEMATIC PHYSICAL MODEL FOR BUILDING VOLUME SIMULATION

TOMOHIRO FUKUDA[1], TOSHIKI TOKUHARA[1] and NOBUYOSHI YABUKI[1]
[1] *Osaka University, Suita, Osaka, Japan*
{fukuda, yabuki}@see.eng.osaka-u.ac.jp, tokuhara.t@gmail.com

Abstract. Both a physical model and VR are three-dimensional expression tools to enable intuitive understanding; however, both have pros and cons. Thus, this research took up the challenge of developing a kinematic physical model system for volume simulation of buildings or a city by using a physical model and VR data integrally. The developed system consists both of hardware which packed 105 lifting rods into a grid (the height of the rods could be changed individually by stepper motors) and of software which calculated the height of each rod from the VR data and lifted the rods. Through conducting verification experiments on the prototype system, a physical urban model could be produced in about two minutes, within acceptable error limits. In conclusion, the proposed method was evaluated as feasible and effective.

Keywords. Kinematic model; physical model; Virtual Reality; rapid prototyping; building volume simulation; interaction.

1. Introduction

1.1. BACKGROUND

This research focuses a physical scale model and Virtual Reality (VR) as an architectural and urban design tool. Both physical model and VR are three-dimensional expression methods, and enable intuitive understanding. A physical model is a three-dimensional (3D) object into which a real space is reduced according to a constant ratio. The strengths of a physical model are that the user can touch the model directly, that several people can examine it at the same time from arbitrary viewpoints, and it allows users to understand the whole city. In contrast, the weaknesses are the limit of expression caused by the reduction, a limitation of the range of production, and that study from the pedestrian viewpoint is difficult. VR is a three-dimensional space expressed in the virtual environment of the computer. The strengths of VR are that a realistic expression by texture mapping is possible, that study from the pedestrian viewpoint is easy, and it can express dynamic urban elements such as people and cars. In contrast, the weaknesses are that it is impossible to touch directly, and that the sense of distance is elusive. Both the physical model and VR have strengths and weaknesses differently as mentioned above. Therefore, in the current presentation, they have been respectively used. Might each weakness be rectified by using the two systems together?

In fact, it is necessary to produce a physical model and VR with the same contents when using them integrally. Their creation requires a lot of work and high cost. Also, if a design plan has been changed in a design study meeting, it is traditionally difficult to immediately regenerate the physical model and VR corresponding to the changed design plan. As an expanding technology to bridge the digital and physical worlds more seamlessly, there is 3D printer technology, which can output a physical model from 3D data such as VR. However, the print speed is still slow at approximately 30 mm/hr in the height direction, and immediate output is impossible.

1.2. PREVIOUS STUDIES

Previous studies on urban presentation system that combined with a physical model and VR are as follows. The tangible user interface (TUI) has been the target of much research as a possible solution to this problem (Ishii and Brygg, 1997; Rom and Surapong, 2009). Tonn et al. (2008) developed an interface with which users can operate a 3D cad model on a real scale with a laser pointer and 3D projector. Fujimon et al. (2004) developed a system that displayed VR contents seen from an avatar after having designed a sensor that could acquire the location information as an avatar of the operator. Nagakura et al. (2006) developed an interactive space browser for architectural designs. Moving its lightweight LCD panel over the plan of a building drawing displays a 3D interior view of the building. Tokuhara et al. (2010) developed a system that linked viewpoint information between a physical scale model and VR using image processing technology. However, both a physical model and VR have to be preliminarily created before running these systems, then, the problem to immediately regenerate the physical model and VR corresponding to the changed design plan still remains as described in Section 1.1.

As a different approach, Makanae et al. (2006) developed a tangible terrain representation system (TTRS) for highway design which can represent a terrain surface by controlling the shape of a stretchable screen used to represent the terrain surface by means of a total of 64 actuators (8x8) and projecting an aerial photograph onto the screen. This system has been able to dynamically generate small scale undulating terrain from VR data. However, adaptation to large scale urban design, which was the theme of this study, was difficult.

1.3. PURPOSE OF THIS STUDY

The main challenges to be derived from the previous studies described in Section 1.2 are as follows. Firstly, a system must be able to synchronize with a physical model and VR at the data level. Secondly, to represent a physical model at urban scale, a system must be able to represent individual buildings of various sizes and heights dynamically. Therefore, in this research, a kinematic physical model system for volume simulation of buildings or city has been developed that uses lifting rods in a grid.

2. Kinematic physical model system design

2.1. GENERAL OUTLINE

Figure 1 shows a conceptual diagram and system flow of the kinematic physical model system. The proposed system is flowed as follows (Figure 1): A user inputs the VR data and reduced scale data that he wants to output the kinematic model. The software calculates the height of each rod of the kinematic model. Then, each rod of the kinematic model moves up and down. Each rod can be individually controlled height to represent volume of a building or city. This kinematic physical model makes it possible to dynamically change the scale, a representation of multiple plans rapidly by inputting the VR data.

This device is connected to the PC that VR model is installed. This device consists of a digital output board, two terminals fastened with screws, a number of rods, a row of motors for lifting rods, rack gears, a motorized slider, a stopper of the rods and developed software to driven them.

The lifting rod system had a row of 15 motors for lifting the rods, and the rods which had completed their lift were fixed by stoppers in series. A stepper motor was used to operate both a row of 15 motors for the lifting rods and a stopper of the rods. Parts in a stepper motor include a number of electromagnets called stators and a permanent magnet called a rotor. When magnetized by applying a voltage to a stator, a rotor is adsorbed and rotated. A process to magnetize the stator is carried out involving periodic voltage changes called pulses. Clockwise and counterclockwise rotations can be performed by pulse waveform. Also, since the rotation angle per pulse is fixed, accurate control can be achieved by the number of pulses. In addition to rotation control by pulse, the rotor is fixed to the stator by continuously energizing the stator electromagnets, so that brake control occurs.

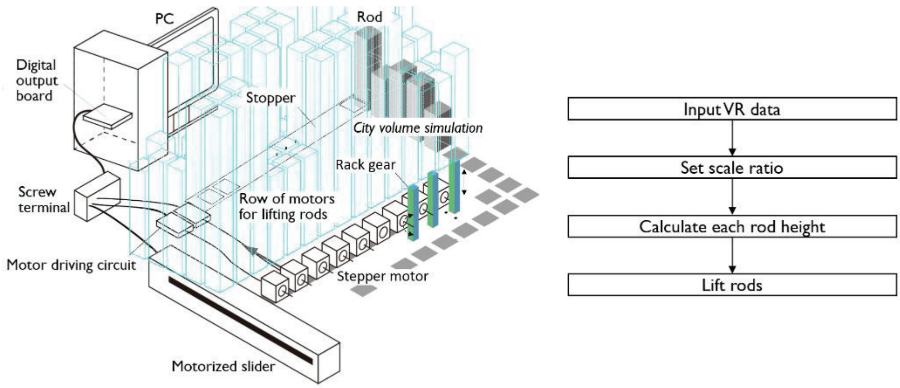

Figure 1. Kinematic physical model system: Conceptual diagram (left) and system flow (right).

2.2. SELECTED DEVICES

The authors used CONTEC DO-128T2-PCI as a digital output board, and CONTEC EPD-100A as a terminal fastened with screws. The DO-128T2-PCI was connected to a desktop PC motherboard by PCI. It was possible to individually control the ON / OFF status of 128 terminals from software on the PC. The terminal control was carried out in an open collector system. The 64 output terminals of EPD-100A were transformed from the 64 output terminals of the digital output board on a one-on-one level. In addition, EPD-100A has 24 ground terminals and eight 5V terminals. Two EPD-100As were used for this system.

The authors used an Oriental Motor PK213PDA as a stepper motor. The PK213PDA is a 2-Phase bipolar stepper motor, has a stator consisting of two electromagnets, and two poles A and B are wired to each electromagnet. Rotation of the motor is made possible by inputting a pulse to these four poles. The input pulse consists of a total of four steps which induce a clockwise and counterclockwise rotation for the poles A and B in the two electromagnets respectively every 5 msec. The rotation angle per 1 step is 1.8 °.

The authors used the Yamazaki N6753 as a lightweight rack gear, under the torque of the stepper motor. Resinous straight gear parts are attached to a resinous frame. The frame of the N6753 has holes at equal intervals to reduce its weight.

The authors used an Oriental Motor ELS2XE020-KP motorized slider. This is a table, the top of which can move with a slider in parallel, with a movable range of 200mm. The moving amount and speed are adjustable by assigning a signal to the six input terminals of the dedicated driver.

The authors used a desktop PC with an Intel Core i7 Quad 2.60GHz CPU, 8.00 GB of RAM, 256 MB of VRAM, running Microsoft Windows 7 Enterprise.

3. Kinematic physical model system fabrication

To fabricate a prototype system, after studying the physical width of the stepper motor and rack gear, the distance between the centers of the rods was designed to be 27 mm, and one side of the rod was designed to be 20 mm. For rod placement, the driving current of a stepper motor was 500 mA, and the total electric capacity of the power supply was 10 A. Therefore, a row of rods was designed to include fifteen rods. Then, since the movable range of the motorized slider was 200mm, the rods could be placed in seven columns. As a result, a total of 105 rods could be placed. The software and hardware developed in this research are described in detail below.

3.1. SOFTWARE

As the software developed in this study, after the rod height calculation process to calculate the height of the center coordinates of each rod after importing 3D data such as VR, the rod lifting process to lift each rod physically by driving the stepper motors was carried out.

In the rod height calculation process (Figure 2), firstly, the maximum surface *Ft* of each object defined in the 3D data was extracted. Secondly, after judging whether the rod center *R* (*RodX*, *RodY*) of each rod was within or beyond the highest surface *Ft* of each object, the rods whose center *R* was located within the highest surface *Ft* were extracted. The value of the highest surface *Ft* was obtained as the height *H* to which the rods were lifted. Thirdly, the number of steps for driving the stepper motor was calculated by dividing the *H* by the amount *Hs* of increase in one step of the stepper motor.

The lifting process of rods was as follows. First, a row of stepper motors for lifting rods was moved parallel to the origin of the motorized slider for system initialization. Second, a row of stepper motors for the lifting rods was moved to a position below the rod row. Third, after lifting up each rod in row to rotate each stepper motor by the number of steps calculated in the rod height calculation process, braking was generated by continuing to energize the stepper motors so that the lifted rods did not fall down. Fourth, the stopper was slid by a stepper motor attached to the frame, and the rods were fixed. Fifth, the stepper motor brake was released. Sixth, a row of stepper motors for lifting rods was translated to the next column of rods. The process from steps one to six was executed for each column.

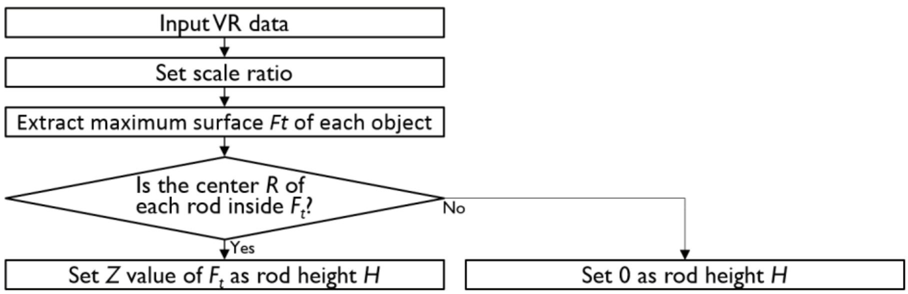

Figure 2. Rod height calculation process.

3.2. HARDWARE

All the hardware is described (Figure 3). The upper surface of the frame was supported by bonded wood to be positioned at a height of 460mm. A stopper module was installed in each column of the frame, and a total of 105 (15x7) rods were inserted into the grid frame. A fall prevention mesh made of balsa wood was installed in the bottom of the frame horizontally. This supported the rods and prevented them falling from the frame when the rods were not fixed by the stopper. There was a layer of stepper motors for lifting rods below the fall prevention mesh. This layer slid under the frame by being fixed to a motorized slider and a caster.

The driving circuit of a stepper motor is described. The ON / OFF control method of the digital output board was an open collector system as described in Section 2.2. The voltage output from the digital output board was not sufficient to drive the motor. Therefore, it was necessary to separately produce a motor driving circuit for boosting the motor driving voltage (Figure 4). The motor driving circuit was composed of transistors required for amplification, diodes for circuit protection, and resistances. In the case of a digital output board using the open collector method, when OFF, the voltage applied to the terminal became unstable, and the behavior of the transistor in the driving circuit also became unstable. Therefore, by connecting the terminal and the power supply with a resistance called a pull-up resistor, the behavior of the transistor was stabilized.

As a row of 15 stepper motors were installed in order to allow 15 rods to lift at the same time. A motor driving circuit, a flat gear, and a rack gear were installed in each stepper motor. Each stepper motor was fixed to the lower surface of an expanded polyvinyl chloride plate, and lifted a rack gear through a circular hole in the upper and lower expanded polyvinyl chloride plates. The height of each rod pushed up by the stepper motor was restricted by the frame and the stopper located on the upper part of the row of stepper motors (Figure 4).

To make the frame, firstly, cypress timbers which were 5 mm wide and thick were assembled in a grid pattern with a 27mm pitch. Two sets of these were joined vertically. In one of the side plates of the frame, seven stepper motors were installed. A threaded shaft was added to the rotation shaft of the stepper motor for these stoppers. As the stoppers, 15 holes with 22 mm in diameter were drilled at 5 mm intervals. At the side of each hole, balsa wood which was 3 mm thick with a sponge was attached. At the plate edge of the balsa wood, a bending clasp with a soldered nut was attached (Figure 4).

The mechanism of the stopper was as follows. The nut of the stopper engaged with the stepper motor shaft fixed by the frame. The stopper slid in the frame by the rotation of the stepper motor. When the stopper slid to the stepper motor side, the rod was fixed because it was supported at three points of the lattices both at the top and bottom of the frame and the stopper. When the stopper slid to the opposite side to the stepper motor, the rod fell since the lattice and the stopper hole of the frame were aligned in a straight line vertically.

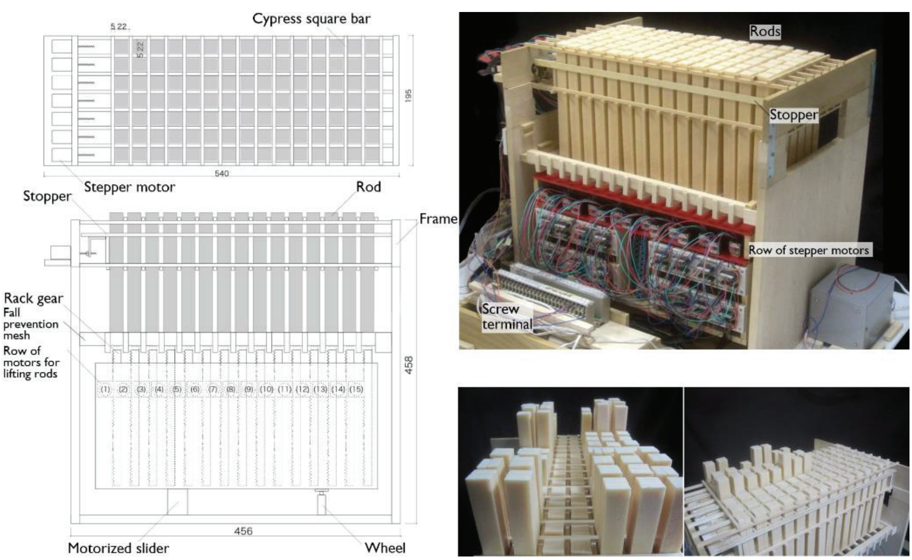

Figure 3. Developed system: Plan view (upper left), elevation (lower left), appearance (upper right), and snapshots when lifting some rods (lower right).

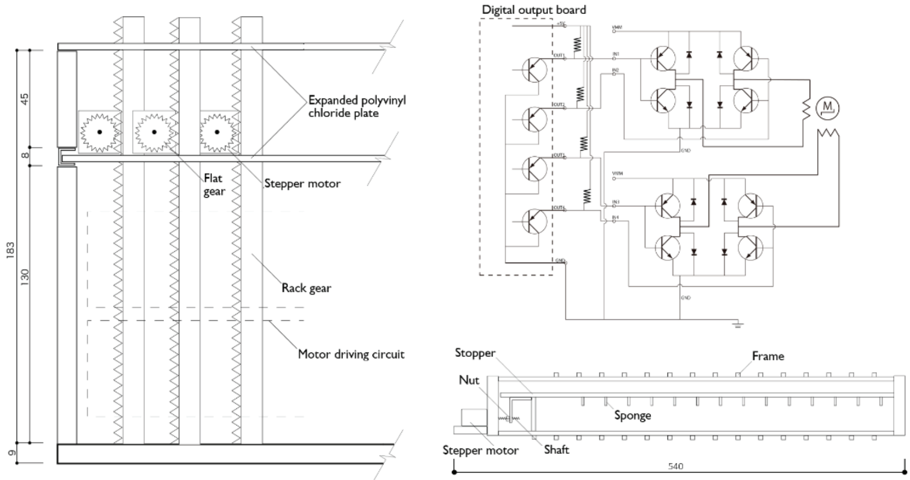

Figure 4. Hardware details: Elevation of row of stepper motors for lifting rods (left), driving circuit of a developed stepper motor (upper right) and elevation of a frame and stopper (lower right).

4. Verification of prototype system

4.1 EXPERIMENTAL METHODOLOGY

To verify the prototype system, the developed system imported a VR model of a virtual city (30m x 18m) which included eight buildings of 10 to 4 meters on both sides of the road (Figure 5), and the accuracy and time required to operate the kinematic physical model were measured.

For accuracy verification, in terms of the horizontal positioning on the plane and height, the theoretical value $T_{x,y,z}$ and the measured value $R_{x, y, z}$ were compared. The scale model to be output was set to 1:100. Furthermore, as regards the horizontal positioning verification, the theoretical values $T_{x, y}$ were defined as the maximum and minimum values of the horizontal and vertical directions in the coordinates of building four corners on a plane surface derived computationally. The measured value $R_{x, y}$ was defined as the Euclidean distance between the corner of the corresponding rods and the origin. Regarding the height verification, with all rods lifted up, firstly, the absolute values of the difference between the measured values R_z and the theoretical value T_z were calculated. Then, the error ratio for T_z was calculated as the deviation ratio D_z below.

$$D_z = | 1 - R_z / T_z | \text{ x } 100 \tag{1}$$

For verification of the output time, the average running time from startup of the software until the halt of the stepper motor for the last stopper was calculated after being measured three times with a stopwatch.

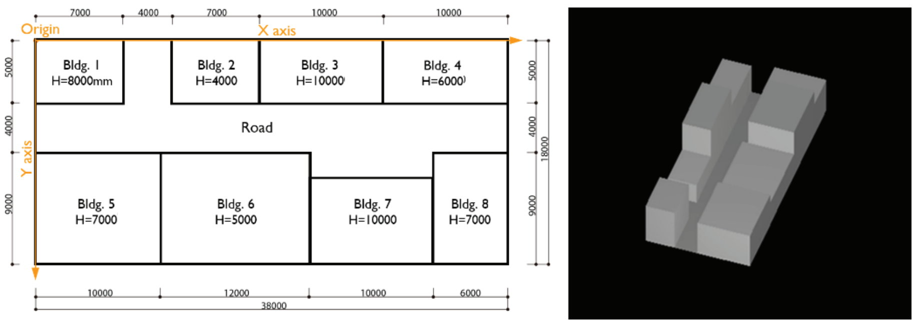

Figure 5. VR data for verification: Plan view (left) and bird's-eye view (right).

4.2 RESULT BY 1:100 SCALE

The minimum error in the horizontal positioning on the plane was 0 mm, maximum 25 mm, with an average of 7.90 mm. These values were within an acceptable error range since the side of the rod was 20 mm in width, and using the central coordinates of the rod to perform inner and outer determination. However, when compared with the traditional physical model, the error was large. As an improvement to achieve the traditional physical model's accuracy, the rod needs to be thinner.

The minimum error of the height was 0 mm, maximum 5 mm, and the average was 1.17 mm. The deviation rate D_z was distributed from a minimum of 0% up to 8.3%, and the average was 2.28%. The average error was comparable to that occurring when a person produced a physical model manually. Also, this error was not a major obstacle when studying urban space (Figure 6).

4.3 CALCULATION TIME

The computation time was 2 minutes 00 second 3. This result showed that the prototype system could produce output in a short time for a certain scale urban model.

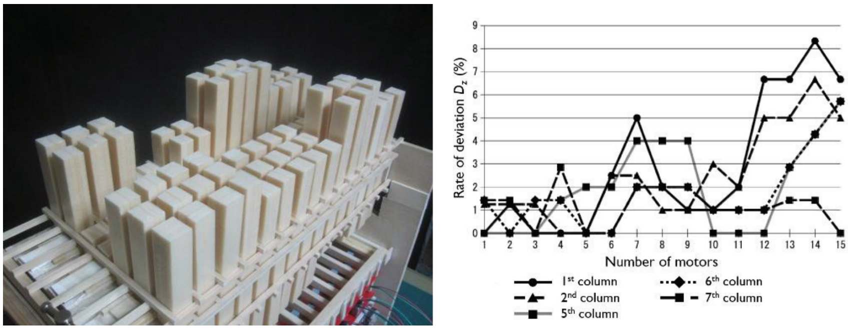

Figure 6. Result: Appearance after lifting at 1:100 scale (left) and rate of deviation D_z (right).

5. Conclusion

This research presented the development of a kinematic physical model system for volume simulation of buildings or a city by lifting rods in a grid. Therefore, hardware which incorporated 105 rods whose height could be changed individually by stepper motors etc. could be developed, along with software which calculated the height of each rod from the VR data and made the rods lift. Through conducting verification experiments for the prototype system, an urban physical model could be produced in about two minutes, with an acceptable margin of error.

In future work, for detailed volume modeling, thinner rods need to be used. Therefore, it is necessary to reduce the size of the parts constituting the hardware such as the stepper motors and rack gear etc.

References

Fujimon, C., Ando, M., Yamashita, J., Yoshida, K., Kuzuoka, H., Hiroe, M.: 2004, Development and Evaluation of Tangible Avatar Interface for VR Space Navigation, Proceedings of Transactions of the Virtual Reality Society of Japan, vol.9 (2), 123-130.

Ishii, H., Brygg, U.: 1997, Tangible Bits: Towards Seamless Interfaces between People, Bits and Atoms, Proceedings of CHI ‘97, ACM Press, 234-241.

Makanae, K., Nakahara, M.: 2006, Development of Tangible Terrain Representation System for Highway Route Planning, Conference Proceedings of Joint International Conference of Computing and Decision Making in Civil and Building Engineering (CD-ROM).

Nagakura, T., Oishi, J.: 2006, Deskrama, SIGGRAPH 2006.

Rom, K., Surapong, L.: 2009, ‚TANGIDESK: A Tangible Interface Prototype for Urban Design and Planning, Proceedings of the 14th International Conference on Computer Aided Architectural Design Research in Asia, 705-714.

Tokuhara, T., Fukuda, T., Yabuki, N.: 2010, Development of a City Presentation Method by Linking Viewpoints of a Physical Scale Model and VR, Proceedings of The 28th eCAADe (Education and Research in Computer Aided Architectural Design in Europe), 747-754.

Tonn, C., Petzold, F., Donath, D.: 2008, Put on Your Glasses and Press Right Mouse Button: AR-Based User Inter action Using Laser Pointer Tracking, Proceedings of 24th eCAADe Conference, 201-208.