

Simulating a Walk of Digital Human Model Directly in Massive 3D Laser-Scanned Point Cloud of Indoor Environments

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Abstract. Recently, human behavior simulations in 3-dimensional environment models have been enabled by the advance in computer performances. However, manually building the 3D models for the simulations are still costly and time-consuming, and the resultant models are sometimes inaccurate and do not necessarily reflect as-built environments. The final goal of our research is to realize the accessibility evaluation of “as-built” environments based on the human behavior simulation. To achieve the goal, in this study, we developed a technology where as-built 3D environment models could be constructed in a fully automatic way from laser-scanned 3D point clouds measured from as-built indoor environments. Additionally, we realized a basic walking simulation function in the as-built environment model represented by the point clouds. The modeling and simulation efficiency and accuracy were evaluated.

Keywords: human behavior simulation, laser scanning, 3D point clouds.

1 Introduction

Recently, studies of human behavior simulations in large-scale environments have been increasing in the area of realistic crowd animations, disaster and evacuation planning and the analyzing of crowd dynamics [1]. Also, a realistic human behavior simulation, even in a 3-dimensional environment, has been enabled by recent advances in computer performance [2]. However, manually building such 3D environment models is still costly and time-consuming, and the resultant models are sometimes inaccurate and do not necessarily reflect as-built environments. The problems become serious as the environments become large-scale. On the other hand, scanning large-scale environments as 3D point clouds was enabled by the progress of 3D laser scanning technology which realizes fast and accurate as-built modeling.

The final goal of this research was to evaluate the “accessibility” of 3D as-built environments based on the human behavior simulation results. Currently, such evaluations are greatly depending on the professionals [3] and still remain quantitative. However, the human behavior simulation could realize a more detailed and quantitative accessibility evaluation. As-built environment models are indispensable for the

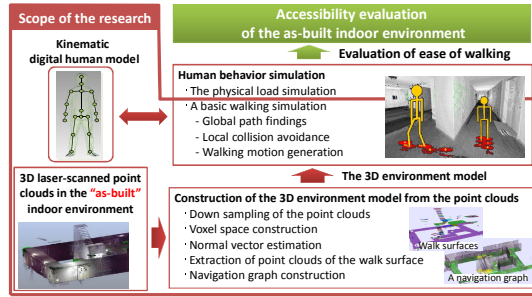


Fig. 1. Overview of the research

simulation. Therefore, as shown in Fig.1, the purpose of this paper is first to develop a technology where the 3D environment models can be constructed in a fully automatic way from laser-scanned point clouds measured from as-built indoor environments.

Moreover, a kinematics-based walk of a digital human model could be directly simulated in the models. The modeling and simulation efficiency and accuracy were evaluated.

As shown in Fig.1, a human behavior simulation consists of the global path findings, the local collision avoidance and the walking motion generation. Therefore, in this study, the walk surfaces for the walking motion generation, a navigation graph for the global path findings, and normal vectors of the down-sampled point clouds for the walking motion generation were automatically generated from the laser-scanned point clouds to build the 3D environment models.

2 Related Work

This research mainly involved three related areas: the 3D environment model construction from laser-scanned point clouds, digital human modeling for gait simulation and the crowd behavior simulation.

In the work of Nüchter [4], floors and walls were automatically recognized from laser-scanned point clouds of indoor environments. Similar work was done by Rusu [5] for recognizing household goods. However, their environment models did not include the essential data structure for the human behavior simulation such as the navigation graph for the global path findings. Many studies have been done for the digital human modeling for gait simulation. The motion-capture-based gait simulation could synthesize the variety of human gait patterns [6]. On the other hand, Chang [7] estimated a physical load in assembly tasks in the workspace using the dynamics-based digital human model. However, if their works are used for the accessibility evaluation, the walking path and footprints in the large-scale environment have to be specified manually which enforces unacceptable workload to the users of the simulation.

For the human behavior simulation, the local collision avoidance and the global path findings are indispensable. Many different methods have existed for the local collision avoidance such as social forces [8], cellular automata [9], and rule-based [2]. However, [8] and [9] did not use the 3D as-built environment models but the as-planned 2D environment ones. Kakizaki [2] proposed the local collision avoidance

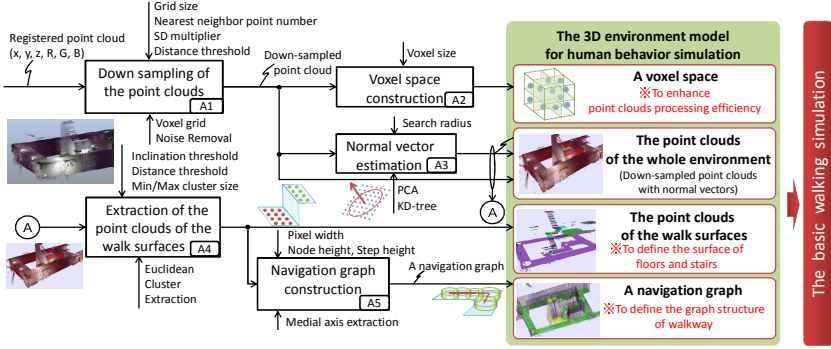


Fig. 2. Construction flow of the 3D environment model from point clouds

algorithm of the evacuation simulation which could avoid obstacles and other humans in the 3D environment models by checking the three occupation-inspection spaces in front of a human model. However, the human movements were limited only to three directions, and lacked the reality of human motion. On the other hand, Pettre [10] proposed an algorithm which constructed a navigation graph for the global path findings. The navigation graph, which represents a free-space and its connectivity, could be automatically generated from the 3D mesh model. However, their navigation graph had to be generated from the 3D mesh model of the environments which becomes hard to construct if the point clouds become too large.

3 Construction of the 3D Environment Model From Point Clouds

For the basic walking simulation, 3D environment models must be first built from 3D laser-scanned point clouds of an as-built indoor environment. Fig.2 shows the construction flow of the models. The model consists of two point clouds (the point clouds of the whole environment and the point clouds of the walk surfaces), the voxel space for efficient management of the massive point clouds and a navigation graph for defining the walkway for humans. The details are described in the following sub-sections.

3.1 Down Sampling Of The Point Clouds (A1), Voxel Space Construction (A2) And Normal Vector Estimation (A3)

Multiple laser-scanned point clouds were first merged to make one registered point cloud. This registered point clouds had many points, and was generally too dense to construct the model. Therefore, it was down-sampled using the voxel grid. In this research, one point per square centimeter was enough for the model. Moreover, outlier points were removed using an SOR filter [11] and Euclidian Cluster Extraction[12].

Then, a bounding box, including all down-sampled point clouds, was spatially and uniformly subdivided into a set of voxel spaces. A subset of point clouds included in a

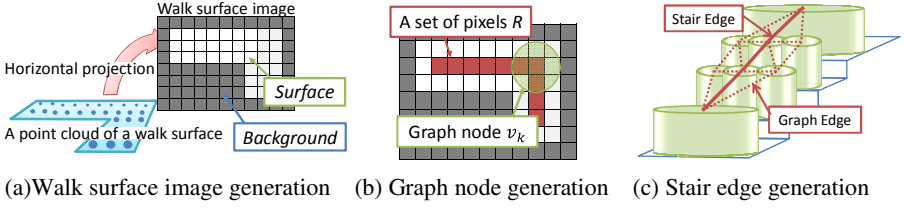


Fig. 3. Navigation graph construction

voxel space was linked to the space. This voxel space helped quicken the neighboring point search of the simulation in the 3D environment model. Finally, normal vectors at the down-sampled points were estimated using principal component analysis of the locally neighboring points [13]. This point cloud with normal vectors was used as a part of the 3D environment model to express the geometry of the whole environment.

3.2 Extraction of The Point Clouds of The Walk Surfaces (A4)

The point clouds of the walk surfaces, such as floors and stairs, were automatically extracted from the point clouds using Euclidian Cluster Extraction. First, if the angle between a normal vector at a point and a vector $\mathbf{v} = [0, 0, +1]$ was smaller than the threshold ε (we set $\varepsilon = 20$ deg.), then the point was extracted as one which could be placed on a horizontal plane. Finally, the point clouds of the walk surfaces were extracted by clustering the points on the horizontal plane using Euclidian Cluster Extraction, and were treated as a part of the 3D environment model.

3.3 Navigation Graph Construction (A5)

Petere [10] proposed a navigation graph for crowd simulation which represented a free-space and its connectivity. In their graph, each graph node represented a free-space and its width, and each edge represented connectivity between two free-spaces. However, their navigation graph had to be generated from the 3D mesh model of the environments, which became hard to construct if the point clouds became too large. Therefore, the following algorithms were newly developed which could automatically create the navigation graph directly from the 3D laser-scanned point clouds.

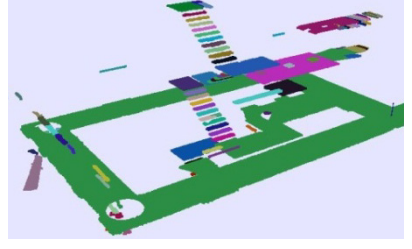
1. **Walk Surface Image Generation:** As shown in Fig.3 (a), a walk surface image was generated by projecting the point clouds of the walk surfaces to a horizontal plane. The image included the *surface* pixel, where at least one point of a walk surface existed, and the *background* pixel, where no points existed.
2. **Walk Surface Image Thinning:** The thinning operation defined by equation (1) was applied to the walk surface image in order to extract the medial axis.

$$t(i, j) = \begin{cases} d(i, j) & (d(i, j) \text{ is local maximum in } 4\text{-neighbor}) \\ 0 & (\text{otherwise}) \end{cases} \quad (1)$$

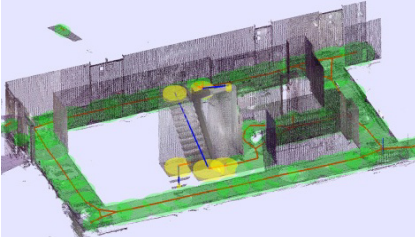
where $T = \{t(i, j)\}$ is an image after thinning, $d(i, j)$ 4-neighbor distance (Manhattan distance) between a pixel (i, j) and its nearest *background* pixel.



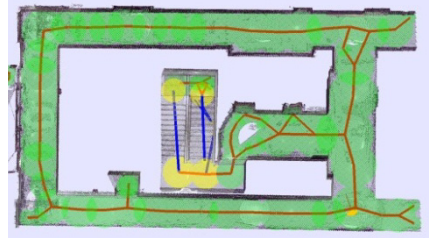
(a) The registered 3D laser-scanned point clouds



(b) The point clouds of the walk surfaces



(c) The navigation graph



(d) The navigation graph (Overhead view)

Fig. 4. The result of constructing the 3D environment model for the walking simulation

3. **Graph Node Generation:** The graph node of the navigation graph was generated in the following steps. First, a set of pixels, R , which satisfies $t(i, j) > 0$ was selected from T as shown in Fig.3 (b). Then, a graph node v_k was generated according to equation (2). Also, the attributes of v_k were evaluated, which include a 2D position vector $Q(v_k)$ and attributes of a cylinder $C(v_k)$ using equation (3).

$$Q(v_k) = \arg \max_{(i,j) \in R} t(i, j) \quad (2)$$

$$\begin{aligned} C(v_k) &= \langle r(v_k), h \rangle \\ r(v_k) &= d(Q(v_k)) \end{aligned} \quad (3)$$

where $r(v_k)$ is a radius of cylinder $C(v_k)$, and h a height of $C(v_k)$. Then, a graph node v_k was inserted to a set of graph nodes, V . Finally, pixels contained in the $C(v_k)$ were removed from R , and these processes were repeated until $R = \emptyset$.

4. **The Graph Edges Generation:** In a set of graph nodes $= \{v_1, \dots, v_n\}$, if the cylinders $C(v_i)$ and $C(v_j)$ have a common region, a graph edge $e_k = (v_i, v_j)$ is defined. A set of all graph edges $E = \{e_1, \dots, e_N\}$ was generated by applying this process to all graph nodes in V .
5. **The Stair Edges Generation:** In a stairway, each stair area becomes small and many small graph nodes are generated. Eventually, many short graph edges are created among the stairs as shown in the dotted line in Fig.3 (c). For simplifying the navigation graph, these short edges were merged to one stair edge. This stair edge enabled efficient path findings on the navigation graph in the simulation.

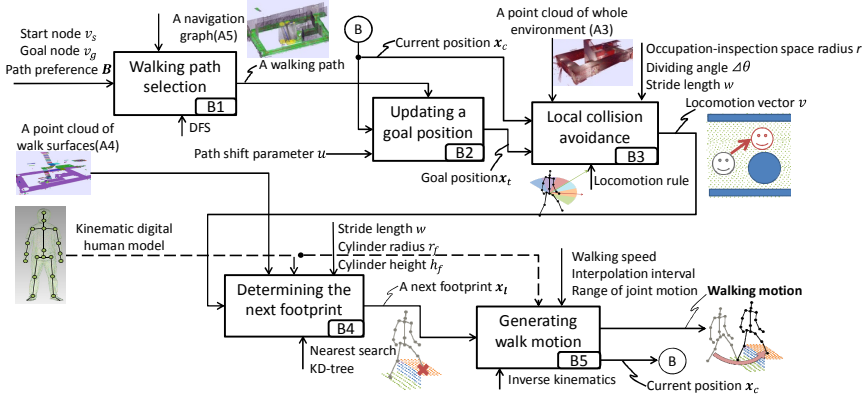


Fig. 5. A basic walking simulation flow

3.4 A Result of Constructing the 3d Environment Model

A result of the construction of the 3D environment models is shown in Fig.4. Fig.4 (a) is the registered point cloud of a building indoors including corridors and stairways. Fig.4 (b) is the point cloud of walk surfaces automatically extracted using this study's method. The stairs could be accurately reproduced as one of the walk surfaces. Fig.4 (c) and Fig.4(d) are the navigation graph. The result showed that the free-space and its connectivity could be successfully modeled in the navigation graph, even in the stairs.

4 Basic Walking Simulation in the 3d Environment Models

To realize a basic walking simulation directly in the 3D environment models expressed by the point clouds, this study used a simple kinematic digital human model [2],[14] with two legs each of which was modeled as a link mechanism with 4 degrees of freedom. As shown in Fig.5, the basic walking simulation using the digital human model is done by the following steps.

1. **Walking Path Selection:** Based on the user-defined start node and goal node, a walking path of the digital human model was automatically found. The walking path was determined by DFS (Depth-First-Search) over the navigation graph based on the path cost and user's preference for the path.

For this purpose, first, all feasible paths from a start node v_s to a goal node v_g were extracted by DFS over the graph. Then, the path cost vector C_i which is defined by equation (4), was evaluated in each path i .

$$C_i = [d_i, \rho_i, b_i] \quad (4)$$

where $d_i \in [0,1]$ = a normalized travel distance along path i .

$\rho_i \in [0,1]$ = a normalized crowd density on path i .

$b_i \in [0,1]$ = a normalized narrowness of path i .

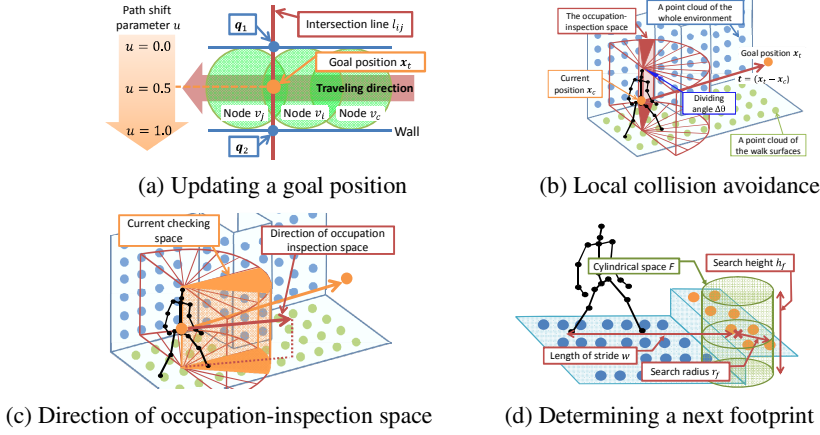


Fig. 6. An algorithm of a basic walking simulation

Finally, a walking path j was selected by equation (5).

$$j = \arg \min_i (C_i \cdot B) \quad (5)$$

where $B = [\beta_1, \beta_2, \beta_3]$ is a user's path preference vector for the path, and each element $(\beta_1, \beta_2, \beta_3)$ ($\beta_k \in [0, 1]$) controls the degree of preferences among travel distance, crowd density, narrowness of the path.

Once a walking path j was selected, the following processes from (B2) to (B5) were repeated until the digital human model reached the goal node v_g .

- Updating Goal Position:** As shown in Fig.6 (a), in order to let the digital human model walk along the walking path, a goal position, x_t , which is a temporary target position of walking, was updated every time when the model walked from a current graph node, v_c , to the next node, v_i . x_t was calculated based on the path shift parameter $u \in [0, 1]$ and an intersection line, l_{ij} , between graph nodes v_i and v_j by equation (6).

$$x_t = (q_2 - q_1)u + q_1 \quad (6)$$

where q_1, q_2 are position vectors of the intersected points between walls and l_{ij} . If the digital human model was made to walk in the center of the walkway, the path shift parameter u set 0.5 .

- Local Collision Avoidance:** A locomotion vector of the digital human model in every step was automatically determined on-the-fly by the study's locomotion rule-based local collision avoidance algorithm. As shown in Fig.6 (b), the locomotion rule determined a locomotion vector by checking obstacles represented by the point clouds of the whole environment in front of the digital human model. The fan-shaped occupation-inspection space was checked for obstacles in order from the front, and side to side. If the space was free, which meant no points existed in the occupation-inspection space, then the locomotion vector was determined as a direction of the current space, as shown in Fig.6 (c).

4. **Determining the Next Footprint:** After the locomotion vector was determined, then the next footprint was found on the point clouds of the walk surfaces. As shown in Fig.6 (d), first, a cylindrical space, F , with search radius r_f and search height h_f , was generated at a point placed on the stride length, w , a head of the current footprint. Then, the point clouds, which represent a walk surface which has a maximum point number inside of F , were extracted from the point clouds inside of F . Finally, the next footprint was determined as a centroid of these point clouds.
5. **Generating Walk Motion:** Finally, all of the leg joint angles were calculated by solving the inverse kinematics to reach the next footprint, and the motion of a walking step was generated by linearly interpolating each of the leg joint angles.

5 Simulation Results

5.1 Walking Simulation Results in the 3D Environment Models

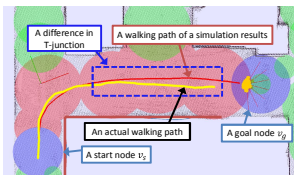
A result of a basic walking simulation in the point clouds is shown in Fig.7. In the figure, the 3D environment models were constructed from the 3D point clouds of Fig.4 which were generated by the scans of one floor of a university building, including two stairs, by a terrestrial laser scanner (FARO Focus^{3D} S120). Fig.7 (a) shows the walking simulation on stairs. This study confirmed that the kinematic digital human model could autonomously climb stairs as shown in Fig.7 (a).

On the other hand, Fig.7 (b) shows the comparison between a walking path obtained from this study's simulation and an actual human walking path in a corner. As shown in Fig.7 (b), the path difference between them was small. But the difference was mainly at the T-junction exit, because a goal position depends on the size of a cylinder, $C(v_k)$.

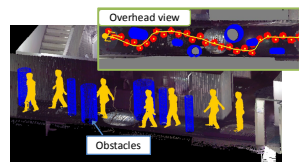
Fig.7 (c) shows the walking simulation results in a corridor, which contained some obstacles on the walk surface (blue objects), and its overhead view. In order to check the effectiveness of the study's local collision avoidance algorithm, a navigation graph was not intentionally used in this case. It was also confirmed that the study's digital human model could also walk directly in the 3D environment models while well avoiding the given obstacles on the walk surface. However, the basic walking simulation in the point clouds still could not work in the region where the laser-scanned point cloud is lacking. To remove this limitation, such a kind of region should be checked and corrected before simulation.



(a) A walking simulation on stairs



(b) A walking simulation in a corner ($u = 0.5$)



(c) A walking simulation in a corridor which contained some obstacles

Fig. 7. The result of the basic walking simulation in the 3D environment models

Table 1. The elapsed time of the modeling and simulation
(CPU: Intel(R) Core(TM) i7 3.30GHz, Memory: 32GB, GPU: GeForce GTX 560 Ti)

Processing		Time [s]	Total [s]
Laser scanning (points: 7,058,731)		16,320	(272 min.)
Registration of point clouds		2,820	(47 min.)
Construction of a 3D environment models	Down sampling of the point clouds (points: 1,043,386)	14.36	19.1
	Voxel space construction	0.14	
	Normal vector estimation	2.40	
	Extraction of the points cloud of the walk surfaces	0.80	
	Navigation graph construction	0.50	
A basic walking simulation		0.016	
Total time of modeling and simulation		19.116	

5.2 Modeling and Simulation Performances

Table 1 shows the elapsed time of constructing the 3D environment model from original point clouds to the basic walking simulation. PCL (The Point Cloud Library) [15] was partly used for the processing of the point clouds, and the OpenGL was used for rendering. The total time of constructing the 3D environment models took 19,159s (319min.). However, the time taken for the laser scanning itself and the registration of point clouds occupied 99% of the total time, and that of constructing the 3D environment models only took 19.1s, which was significantly faster than manual modeling. Moreover, the fast rate of a basic walking simulation was archived (0.016s), and a frequency of a basic walking simulation with rendering process reached about 40 to 60 fps, which fully enabled real-time simulation.

6 Conclusions

In this study, a new method was developed which enabled automatic and efficient construction of the 3D environment models for human behavior simulation from 3D laser-scanned point clouds. In addition, a basic walking simulation was realized directly in the models using a kinematic digital human model. It was confirmed that the modeling process was quite fast and the simulation frequency was enough for real time application. However, the region where the laser-scanned point cloud was lacking should be detected. Moreover, the physical load simulation based on the dynamics [7] and the expansion of a single human walking model to the crowd simulation are needed for the accessibility evaluation. These remain as our further work.

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