Title:

Direct Generation of Cartesian Grid for As-built CFD Analysis from Laser Scanned Point Clouds

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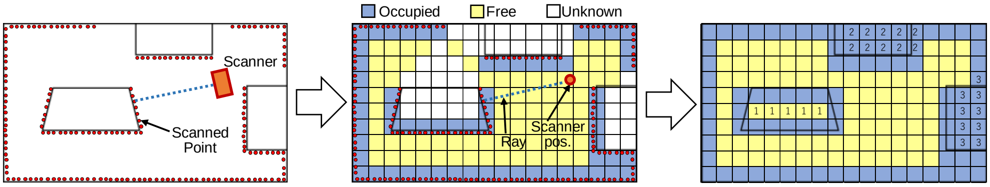
Introduction:

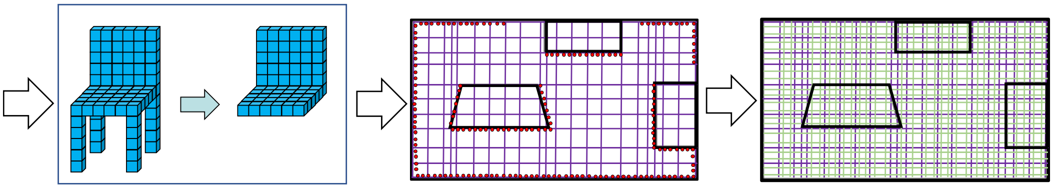
In recent years, numerical simulation of heat and air flow in indoor spaces using 3-dimensional Computational Fluid Dynamics (3D CFD) has begun to spread in architecture and environmental engineering. For the 3D CFD analysis, currently it is necessary for engineers to build a 3D CAD model of a space to be analyzed, and then to generate a grid for the analysis from the CAD model. On the other hand, as the regulations of energy-saving efficiency in buildings have been strengthened and number of repair works of air conditioning equipment is increasing, the demand for "as-built" CFD analysis is also rapidly increasing where the heat and air flow inside indoor spaces in existing buildings have to modelled and analyzed to rationalize the repair works. Accordingly, CFD grids for as-built CFD analysis must be generated that reflect the existing geometries of an indoor space to be analyzed. However, time-consuming manual operations are still required to measure the existing space, to build an accurate as-built 3D CAD model of the space, and to generate a CFD grids that fit with the CAD model. Even if a 3D laser scanner is introduced to improve measurement efficiency, it is substantially impossible to generate a complete as-built 3D CAD model of the existing spaces from the scanned point cloud in a fully automatic and stable manner.



Laser scanned points of an indoor space

Voxel-based Spatial Occupancy Classification

Resolving Unknown Occupancy States of Occluded Spaces



Simplification of Detailed Geometries

Estimation of Object Boundary grid points

Generation of unevenly-spaced Cartesian Grid

Fig. 1: Processing pipeline of our grid generation method from laser scanned point clouds.

To solve the issue, the purpose of this study is to develop a method for automatically generating the analysis grid for "as-built" CFD analysis directly from laser-scanned point clouds of the existing indoor space without creating any 3D CAD model. In the proposed method, unevenly-spaced Cartesian grid can be generated from the point clouds, because it has the excellent stability of analytic calculations, efficiency of grid point numbers, easy control of grid resolutions and geometric reproducibility of object shapes, and thus is widely used as a grid of indoor CFD analysis.

To the knowledge of the authors, there is little research on automatic grid generation for as-built CFD analysis of indoor or outdoor spaces. In the work of [5], they created a town-wide CFD grid for urban thermal environment analysis from laser-scanned point clouds. However, they must manually create a 3D CAD model of the town from the point clouds to generate the grid and do not propose any automation solution to streamline the process. On the other hand, there has been considerable research on automatic grid generation for CFD analysis [4], but they all assume that 3D watertight CAD models or triangular mesh models are given in advance for the grid generation.

Unlike the previous researches, as shown in Fig.1, our method first performs the voxel-based the spatial occupancy classification of the space using the scanned point clouds, resolves the unknown occupancy of occluded spaces, simplifies the detail geometries, estimates the object boundaries and finally generate the unevenly-spaced Cartesian grid. The details of our proposed method are described in the following sections, and the validity of the method is verified by a case study in which a simulated laser-scanned point clouds and commercial CFD simulation software are used along with the system.

Functional Requirements:

The requirements from the aspect of the grid generation from laser-scanned point clouds are summarized as follows. (1) The object surface and space should be correctly distinguished and gridded only based on the point clouds. (2) The spatial occupancy of occluded space caused by laser scanning should be estimated plausibly. (3) Some special objects (heat source, louver, etc.) to which the boundary conditions are added should be automatically detected in the point clouds. In addition, the requirements from the aspect of unevenly-spaced Cartesian grid generation are shown as follows. (4) The adjacent grid width must be monotonically increasing with distance from an object surfaces, and the grid width ratio must be less than the threshold common ratio r (usually less than 2). (5) The geometry of fine details of the object surface unnecessary for analysis should be ignored or approximated in the grid as needed.

Among them, the requirements of (1), (2), (4) and (5) are realized in this study, and (3) remains as a future work. The technical contents how to realize them are outlined as the following sections.

Grid Generation Algorithm from Laser Scanned Point Clouds:

Voxel-based Spatial Occupancy Classification

First, the indoor space to be analyzed is partitioned into voxels, and the space occupancy of each voxel is classified by performing the ray-casting between a voxel and the line connecting a scanned point with the scanner position. In the process, the occupancy state of all voxels is initialized as *unknown*. Then the cells with any scanned point are set as *occupied*, and those intersected with the ray are set as *free*. The process is performed by our modified version of OctoMap[2].

Resolving Unknown Occupancy States of Occluded Spaces

In laser scanning, the *unknown* voxel always remains where any scanned point cannot be acquired due to the occlusion. However, the *unknown* voxel is not allowed for generating CFD grid, and unfortunately it is impossible for the system to uniquely classify the real occupancy state of the *unknown* voxel. To solve the uncertainty, in this study, the *unknown* voxel clusters are graphically shown to the user first, and then the user is prompted to interactively assign *free* or *occupied* state to those clusters. For this purpose, the connected *unknown* cells are automatically pre-clustered using a 3D labeling algorithm. The user interaction is performed with the visualization software (ParaView [3]).

Simplification of Detail Geometries

In CFD analysis, thin columnar shapes with small cross-sectional areas against the flow direction (e.g. chair legs) are often ignored in the grid generation from the efficiency aspect. So, the *occupied* voxel

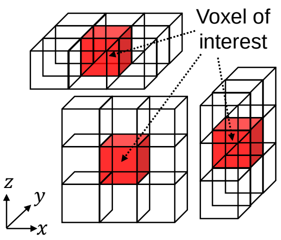
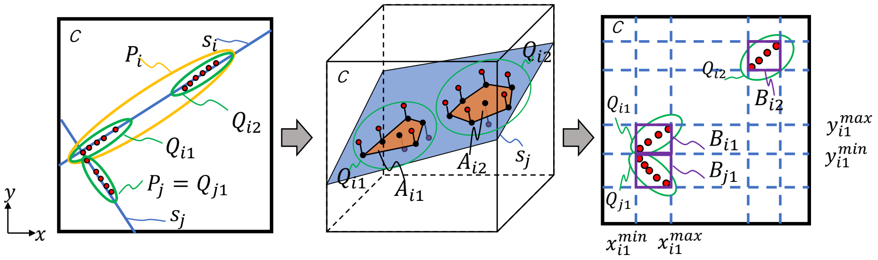


Fig. 2: Three structuring elements of the morphological operator.



(a) Extracting plane elements and inlier point sets

(b) Evaluating the area of the convex polygons

(c) Creating bounding boxes in each point sets

Fig. 3: Estimation of object boundary grid points.

representing the thin shape is changed to *free* voxel by using the following 3D morphological operation. First, the voxel space is scanned with the 3 × 3 × 1 structuring element shown in Fig. 2, and if one or more *occupied* voxels exist in the element, the voxel of interest is labeled as *occupied*. Next, the space is scanned again with the same element, and if there is one or more *free* voxels in it, the voxel of interest is labelled as *free*. Then, these operations are repeated. Finally, these operations are performed independently for three different structuring elements shown in Fig. 2, and the voxels that represent *free* for all structuring elements is final labeled as *free*.

Estimation of Object Boundary Grid Points

The detailed position of the object boundary surface existing in an *occupied* voxel is then estimated as shown in Fig. 3. First, we estimate the least-square plane elements $s_i \in S_c$ that fit the points in the voxel by RANSAC (Fig. 3 (a)). Moreover, we perform the Euclidian clustering of each inlier point set P_i of s_i, and partition P_i into the sub-point sets $Q_{i1,}Q_{i2,\dots}$ (Fig. 3 (a)). Next, we project the sub-point set Q_{ij} onto the plane s_i and evaluate the area of its convex polygon A_{ij} (Fig. 3 (b)). If A_{ij} is greater than or equal to a threshold τ_{ij}, we generate an axis-aligned-bounding-box B_{ij} that bounds Q_{ij}, and we insert the maximum and minimum coordinates $(x_{ij}^{min}, x_{ij}^{max})$, $(y_{ij}^{min}, y_{ij}^{max})$ *and* $(z_{ij}^{min}, z_{ij}^{max})$ of B_{ij} to the elements of the boundary sequences X_L, Y_L, Z_L. The coordinates $(x_l, y_m, z_n) \in X_L \times Y_L \times Z_L$ finally constitutes each grid point on object boundaries. Finally, if an interval between two consecutive elements in the sequence is smaller than the threshold, it is integrated into one element.

Generation of unevenly-spaced Cartesian Grid

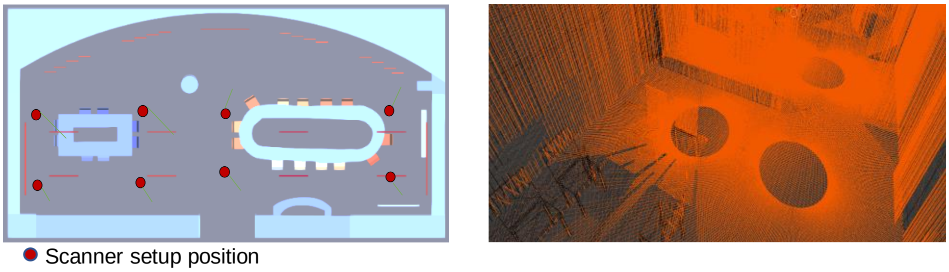
Based on the estimated grid points of the object boundaries, the unevenly-spaced Cartesian grids included in a *free* voxel are calculated independently along x, y, and z directions. The fluid flow velocity changes greatly as it approaches the object boundary, so a fine grid is needed near the boundary. Accordingly, the grid width $d_n = (u_n - u_{n-1})$ is determined by the following Eqns. (1) to (3) such that the interval between two consecutive grid points increases according to the adjacent grid width ratio r:

$$d_n = d_{min} \cdot r^{n-1} \tag{1}$$

$$u_n = \begin{cases} x_l + \dfrac{d_{min}(r^n - 1)}{r - 1} & (d_n < d_{max}) \\ x_l + u_{n^*} + d_{max}(n - n^*) & (d_n \geq d_{max}) \end{cases} \tag{2}$$

$$n^* = \left\lfloor \log_r \frac{d_{max}}{d_{min}} + 1 \right\rfloor \tag{3}$$

where d_{max} and d_{min} are the maximum and minimum target grid width respectively. Finally, for the generated grid points, the grid points included in an *occupied* voxel or existing at the object boundary are labeled as "object", and the other grid points are labeled as "space".



(a) 3D indoor space model for laser scan simulation (Top view)

(b) The simulated scanned point clouds

Fig. 4: Estimation of object boundary grid points.

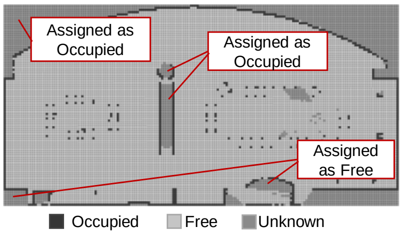


Fig. 5: Spatial occupancy classification results and the interactive occupancy assignments to the unknown cell clusters.

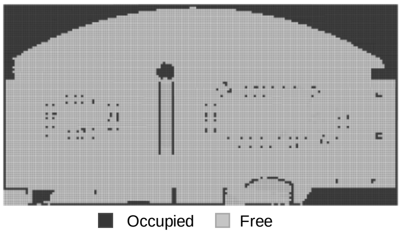


Fig. 6: Spatial occupancy classification results after resolving the unknown occupancy states.

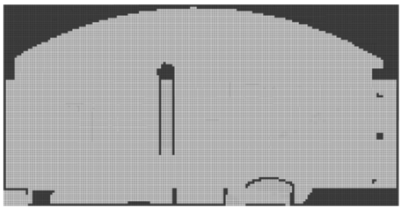


Fig. 7: Spatial occupancy classification after simplifying the detail geometries.

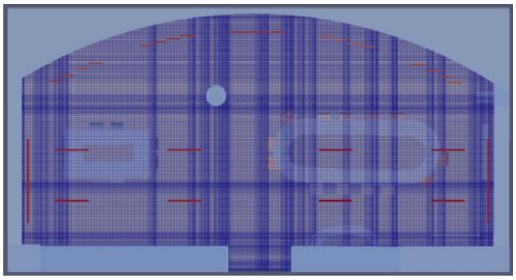


Fig. 8: Unevenly-spaced Cartesian grid generated from the voxel of Fig. 7.

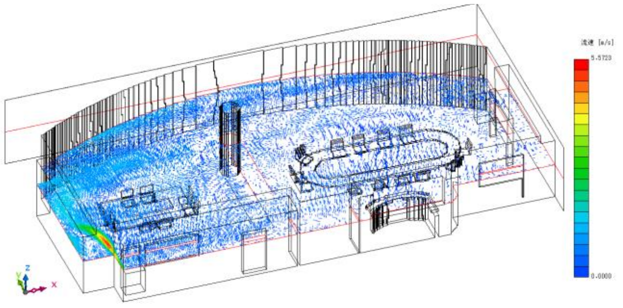


Fig. 9: Air flow simulation result using the Cartesian grid of Fig. 8.

Case Study of Grid Generation and CFD Analysis:

Grid Generation from Simulated Laser Scanned Point Clouds

Laser scan simulation by using the robot sensor simulation software BlenSor [1] was performed on the 3D CAD model of an indoor space shown in Fig. 4 (a meeting room including furniture with a width of 17.5 m, depth of 9.0 m, and height of 2.6 m), and the simulated point clouds are generated. The scanner model was placed at eight different locations in the room shown in Fig. 4 (a), and eight different scanned point clouds of about 540,000 points/scan were obtained as Fig.4 (b).

Fig. 5 shows the spatial occupancy near the floor generated from the point clouds when the voxel resolution is 0.1m. After interactively inputting the occupancy state of a few *unknown* cell clusters caused by the occlusions as indicated in Fig. 5, the occupancy states of these clusters can be completely determined as shown in Fig. 6. Then, the detail geometry was automatically simplified, and the final occupancy state was obtained as shown in Fig. 7. As shown in these figures, the unnecessary details for analysis such as the chair legs have been deleted in the voxel space correctly.

Finally, as shown in Fig. 8, the unevenly-spaced Cartesian grid was automatically generated from the voxel in Fig. 7. The parameters of the grid generation were specified as d_{max}= 0.1m, d_{min} = 0.025m, r =2, τ_{ij} = (area of an equilateral triangle with a side of $5\sqrt{2}$cm). The number of grid points in each orthogonal axis was 559 points in the width, 355 in the depth, and 98 in the height direction. The grid generation time was 6 min 46 sec that does not include the user interaction time. The maximum and minimum grid widths in each axis were 0.131 and 0.025 m in x, 0.1 and 0.025 m in y, and 0.1 and 0.025 m in z axis.

CFD Simulation using the Automatically Generated Cartesian Grid

Next, a simple air flow velocity analysis of the air conditioning system was performed with CFD simulation software (scSTREAM [6]) using the unevenly-spaced grid generated above. The analysis result was shown in Fig. 9. The air inlet was placed on the bottom of the left wall, and the outlet was on the entire right wall. The velocity peak appeared near the inlet. The CFD simulation took 5h32min for predicting the phenomenon for 33sec.

To confirm the results above, the similar flow analysis using a dense equally-spaced Cartesian grid was performed for comparison. The grid width was 0.025m which was same as the minimum grid width of the automatically generated unevenly-spaced grid from the laser scan. The number of grid points was 700 points in the width, 360 in the depth and 104 points in the height. The analysis time was 6h03min under the same condition. The absolute difference in flow velocity between the equally-spaced and unevenly-spaced grids was less than 1% of the velocity in the evenly-spaced grid. It concluded that the unevenly-spaced grid generated from the laser scan using our method can be used for CFD analysis in the same way as the dense equally-spaced grid. The total number of the unevenly-spaced grid points reduced to 75% of that of the dense equally-spaced grid.

Conclusions:

A method to directly generate the unevenly-spaced Cartesian grids from the laser-scanned point clouds of the existing indoor space was proposed for as-built CFD analysis. The method do not require any 3D CAD model in the grid generation. And it was confirmed that the CFD analysis could be conducted by using the simulated scanned points and the proposed method. The comparison of the analysis between dense and evenly spaced grids also showed that the analysis accuracy using the unevenly-spaced Cartesian grid with a smaller grid size obtained by our method was sufficiently ensured.

Future tasks include the grid generation and CFD analysis with actual laser-scanned point clouds. In that case, the robustness of the grid generation against the measurement errors and occlusions of the laser scan should be investigated more.

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