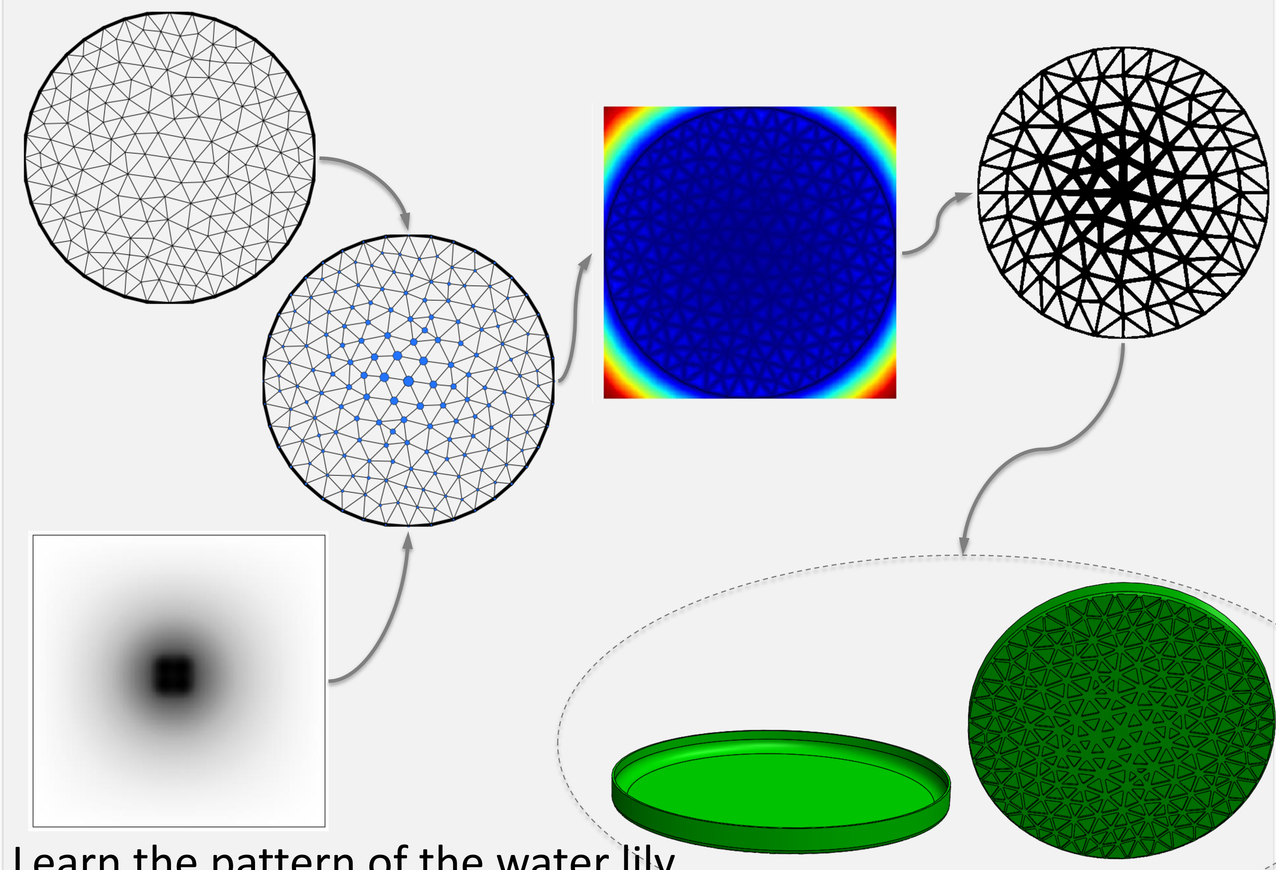
What's the secrete of the water lily?

Design of Functional Lattice Structure with Variable Density Distribution for Additive Manufacturing

Weighted Distance Field Based Method

Student: Wenjin Tao   Faculty Advisor: Dr. Ming C. Leu   Mechanical and Aerospace Engineering Department



Learn the pattern of the water lily using the proposed method.

OBJECTIVE

The purpose of the work described in the present paper is to establish an efficient approach to model 2D lattice structure with variable density distribution that can be fabricated by AM processes. This approach is flexible enough to be applied to any types of 2D lattice structures.

To realize the flexibility of applying this expected method to any kind of lattice structure, it requires:

- Different kinds of lattice structure should be effectively represented by some general formats or methods.
- Local density of the lattice structure should be effectively represented and easily regulated.
- Because 3D lattice design is the next step of this research, this expected method should have the potential to be easily extended to 3D space.

BACKGROUND

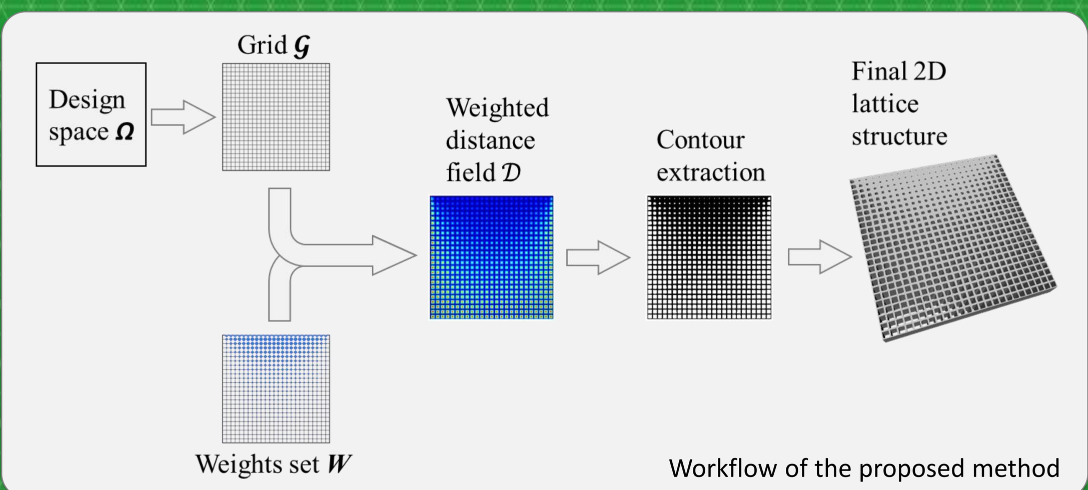
To fully deploy the design and fabrication flexibilities enabled by AM technology, regulation of local relative density has been introduced by several researchers into lattice structure design. It allows the local structures and desired properties to be varied spatially, which could lead to optimized functionalities or characteristics. ***However, existing CAD systems are inefficient in design of lattice structure with variable density distribution, and current studies have barely proposed any general methods to address such issues***. Some related methods are:

- Combining sub-lattice-structures which have different densities.
- For a lattice structure created by using an implicit surface based method, the density gradient can be introduced by modifying its control equation.
- Integrating the topology optimization with the lattice structure pattern design for optimal performance.

METHODS

Therefore, to satisfy those above requirements, the proposed solutions are:

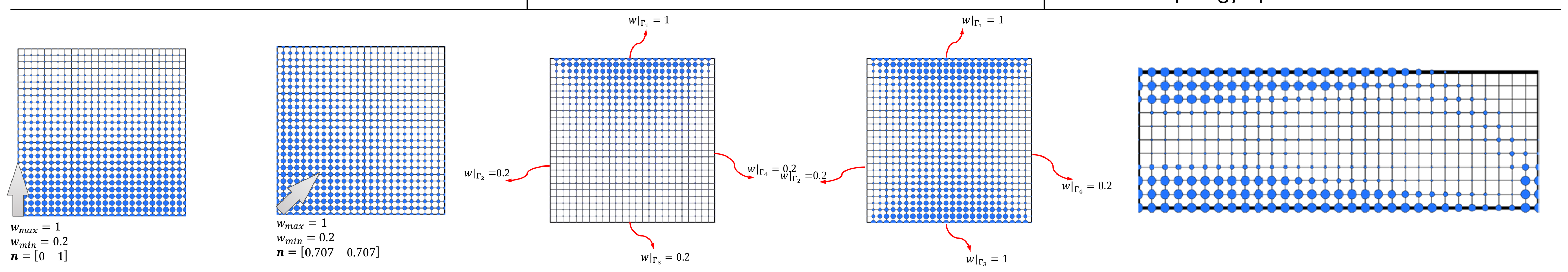
- Use grid to represent the framework of the different kinds of lattice structure.
- Use finite discrete scalars to represent the density distribution.
- Introduce distance field to fit for any type of grid.
- Utilize weight to adjust the local distance field of a certain node's location to realize the desired density distribution.
- Obtain the cross-section shape from the weighted distance field.



Workflow of the proposed method

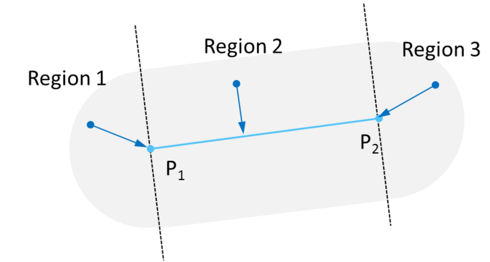
Weights Set Calculation

The weight of each grid node is to adjust the distance field from a certain location in the design space to the lattice structure. In this paper, the weight value can change from 0 to 1 $w \in [0,1]$, 1 means no weighted effect at this node, and decreasing the weight expands the local distance field.



Weighted Distance Field Calculation

The distance field of a grid of lattice structure represents the nearest distance from a certain location to the nearest segment in such grid.



Distances from certain locations to a segment P_1P_2

As a grid contains many segments, to find the distance from a given point to this grid, the distances from a give point to all the segments need to be compared. The smallest value is taken as the resulted distance. For the grid of a lattice structure whose segments amount is *nSeg*:

$$Dist_{grid} = \min_{i \in nSeg}(Dist\_seg_i)$$

Algorithm 2: **function** CalcDist(g, p) **returns** d

Input: Grid g with $nSeg$ segments $\left\{\underbrace{\left(p_1^{(1)}, p_2^{(1)}\right)}_{segment\ 1}, \cdots, \underbrace{\left(p_1^{(nSeg)}, p_2^{(nSeg)}\right)}_{segment\ nSeg}\right\}$, given point $p(x_p, y_p)$

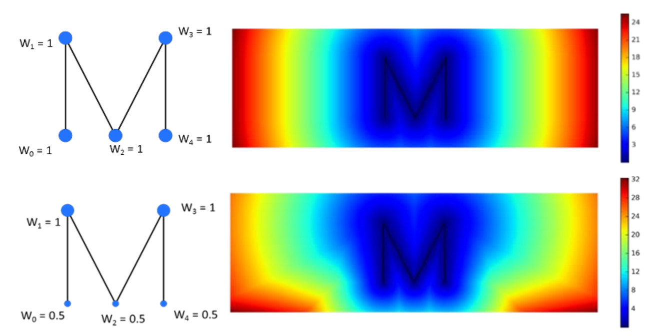
Output: Distance d from the given point to the grid

1. $d \leftarrow d_0$ {Initialize d with a large value}
2. **for** i = 1 to $nSeg$ **do**
3. $r = \frac{\left(x_2^{(i)}-x_1^{(i)}\right)\left(x_p-x_1^{(i)}\right)+\left(y_2^{(i)}-y_1^{(i)}\right)\left(y_p-y_1^{(i)}\right)}{\left(x_2^{(i)}-x_1^{(i)}\right)^2+\left(y_2^{(i)}-y_1^{(i)}\right)^2}$
4. **if** $r \le 0$ {p in region 1} **then**
5. $d' = \sqrt{\left(x_p - x_1^{(i)}\right)^2 + \left(y_p - y_1^{(i)}\right)^2}$
6. **else if** $r \ge 1$ {p in region 3} **then**
7. $d' = \sqrt{\left(x_p - x_2^{(i)}\right)^2 + \left(y_p - y_2^{(i)}\right)^2}$
8. **else** {p in region 2}
9. $d' = \frac{\left|\left(y_2^{(i)}-y_1^{(i)}\right)x_p-\left(x_2^{(i)}-x_1^{(i)}\right)y_p+x_2^{(i)}y_1^{(i)}-y_2^{(i)}x_1^{(i)}\right|}{\sqrt{\left(x_2^{(i)}-x_1^{(i)}\right)^2+\left(y_2^{(i)}-y_1^{(i)}\right)^2}}$
10. **end if**
11. **if** $d' < d$ **then**
12. $d \leftarrow d'$
13. **end if**
14. **end for**
15. **return** d

Algorithm 3: **function** CalcWDist(g, p) **returns** d {Same with Algorithm 1 except the following lines}

5. $d' = \sqrt{\left(x_p - x_1^{(i)}\right)^2 + \left(y_p - y_1^{(i)}\right)^2} \Big/ w_1^{(i)}$
7. $d' = \sqrt{\left(x_p - x_2^{(i)}\right)^2 + \left(y_p - y_2^{(i)}\right)^2} \Big/ w_2^{(i)}$
9. $d' = \frac{\left|\left(y_2^{(i)}-y_1^{(i)}\right)x_p-\left(x_2^{(i)}-x_1^{(i)}\right)y_p+x_2^{(i)}y_1^{(i)}-y_2^{(i)}x_1^{(i)}\right|}{\sqrt{\left(x_2^{(i)}-x_1^{(i)}\right)^2+\left(y_2^{(i)}-y_1^{(i)}\right)^2}} \Big/ \left(w_1^{(i)} + r\left(w_2^{(i)} - w_1^{(i)}\right)\right)$

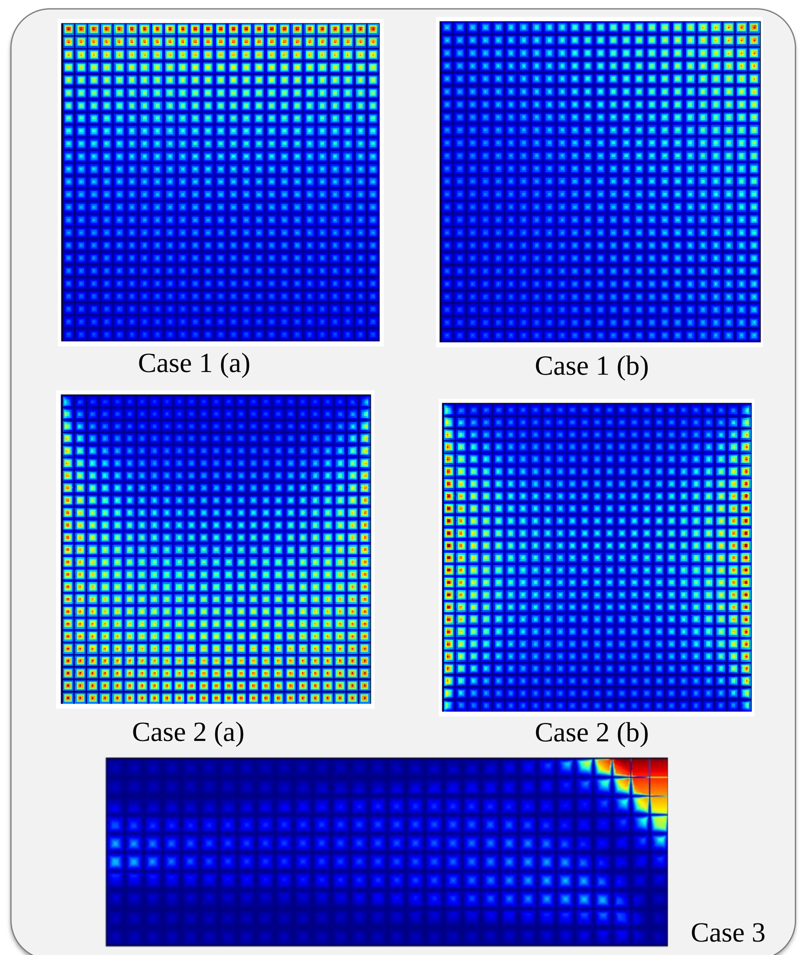
Here, a weight is used as a factor to linearly tune the distance obtained in the previous step. In regions 1 and 3, the weighted distance is resulted from multiplication of the original distance by the weights of their corresponding nodes. In regions 2, a linear interpolation is used to calculated the weighted effect. The pseudocode is listed in Algorithm 3.



Weighted effect on the distance field

Results of the WDF and Cross-section of the Lattice Structure

The proposed approach has been implemented using the Python language on a PC. The developed program successfully obtains the weights set and the weighted distance field is calculated, as shown in the following figures on the leftside.



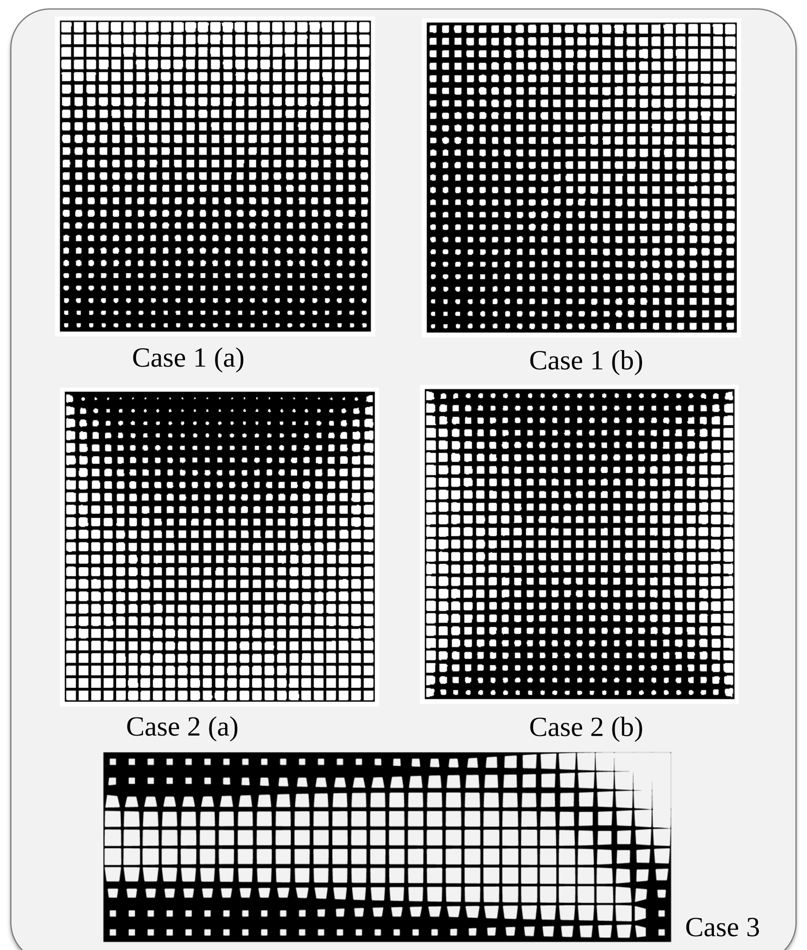
Then a certain isoline of the contour is extracted from weighted distance field to satisfy the initial volume (area for 2D) target. Area calculation and contour iteration algorithms (Algorithm 4) are used in this process. Figures on the rightside show the resulted 2D geometry which is extracted from its weighted distance field and satisfies the area target (area factor = 0.5).

Algorithm 4: **function** ExtractIsoline($\boldsymbol{D}$, f) **returns** l

Input: Distance field $\boldsymbol{D}$, prescribed volume fraction f

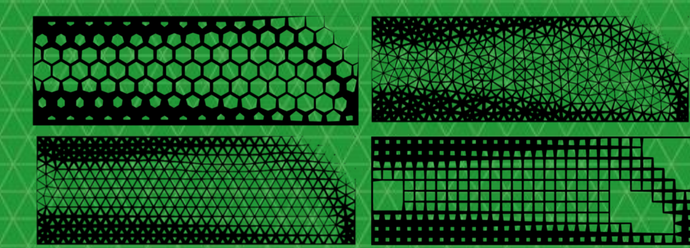
Output: Isoline l

1. $l \leftarrow l_0$
2. **while** $\left|\bar{f}_i - f\right| > \epsilon$ **do**
3. $l_{i+1} \leftarrow l_i + \delta$
4. **end while**
5. **return** l



SUMMARY

- This paper presents a Weighted-Distance-Field based method for modeling 2D lattice structure with variable density distribution.
- Since the cross-sectional geometry of the lattice structure is extracted directly from the weighted distance field, instead of time-consuming and labor-intensive Boolean operation, the proposed method significantly reduces workflow complexities and can be applied to any grid-based 2D lattice structures.



- This approach has been implemented and several examples are demonstrated in the paper. The density distribution of a lattice structure can be tuned flexibly by changing the weights set. Topology optimization methods also provide a solution to obtain the weights set based on the variable of density of its results.
- The proposed approach can be further developed to regulate the density distribution of a lattice structure in 3 dimensions. To model a 3D lattice structure with variable density distribution, a 3D weights set is needed and the iso-surface of the desired lattice structure should be extracted from the 3D weighted distance field. As far as we know, the computing efficiency would be a big challenge in appending the extra dimension.
- By tuning its architecture and density distribution, some other behaviors (e.g. elastic deformation, energy absorption, heat sink), could be regulated accordingly. This is a promising direction in this area and needs more investigation.

ACKNOWLEDGEMENTS

This research work was supported by the Intelligent Systems Center at Missouri University of Science and Technology.

PUBLICATIONS

Design of Lattice Structure for Additive Manufacturing, W Tao, MC Leu, 2016 International Symposium on Flexible Automation, Cleveland, 333-340

Intelligent Systems Center