Functionalized Surface Features for Sunlight-Capture Building Façades

Khalid M. Mosalam I Aashish Ahuja I Tarek I. Zohdi

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Abstract

An important emerging energy application is photovoltaic conversion by capture of natural sunlight. The most critical step of trapping light can be accomplished by functionalizing the surface with features, which includes Winston Cones or fine scale microstructural rods. Here we discuss methods to model these features and hence, obtain an insight into how these systems will operate when exposed to light.

Introduction

The main motivation is to model the optical response of surfaces that has been modified with addition of scatterers or features capable of trapping sunlight and concentrating it over a certain area. Specifically, we are interested in the flow of optical energy, that is the irradiance through these features.

Geometrical Ray-Tracing

Ray-tracing is a method that is employed to produce rapid approximate solutions to wave equations for high frequency/small wavelength applications. Essentially, ray-tracing methods proceed by initially representing wave fronts by an array of discrete rays. Thereafter, one tracks the changing trajectories and magnitudes of individual rays which are dictated by the *Fresnel conditions* in case a ray encounters a material interface. In our current work, it is assumed that the length-scale of the surface features are large enough, relative to the optical wavelength, such that the reflections are coherent and do not diffuse, thus allowing ray-tracing theory to be employed. Specifically, the scatterers and surface features of the cones that we are considering are larger than the wavelength of visible light: $0.38\ \mu m \le \lambda \le 0.78\ \mu m$

Topology Optimization

Topology optimization is a mathematical approach that optimizes material layout within a given design space, for a given set of loads and boundary conditions such that the resulting layout meets a specific optimal objective. The method that we implement to achieve our final configuration for a given layout is referred to as *Bi-Directional Evolutionary Structural Optimization* (BESO). It offers us two main advantages over traditional ESO which makes it more suitable for our application. These advantages are:

1) The addition and removal of material is controlled by one important parameter, namely the *removal ratio of volume*. Traditional ESO rely on two parameters, namely *rejection ratio* (RR) and *evolutionary rate* (ER), to control the optimal design.
2) The final design is independent of the initial design, making the optimization algorithm more robust.

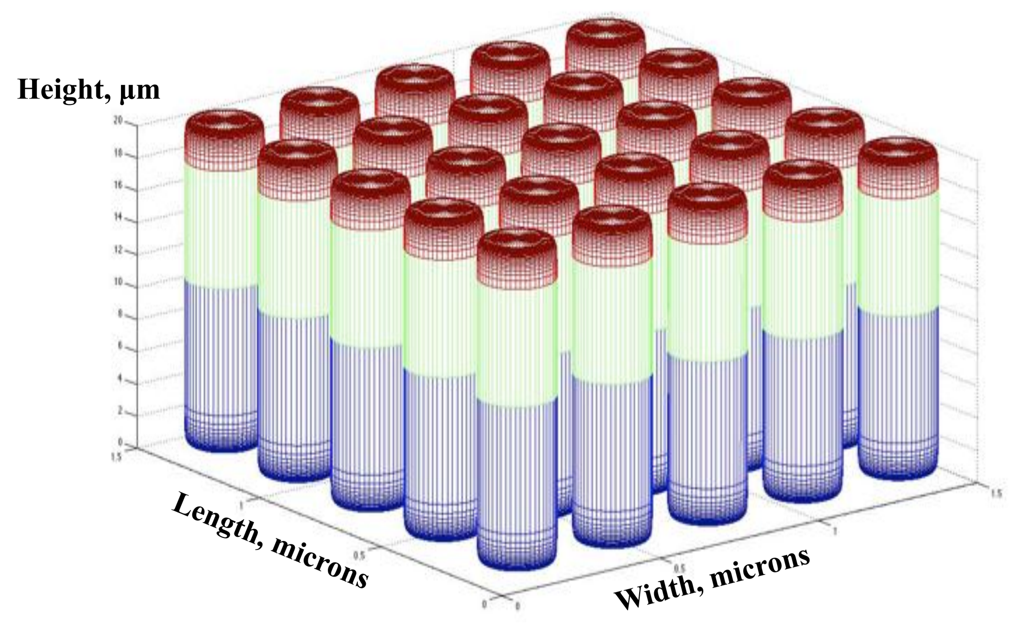

Figure 1. A panel consisting of N=25 micro-rods derived from super-quadrics.

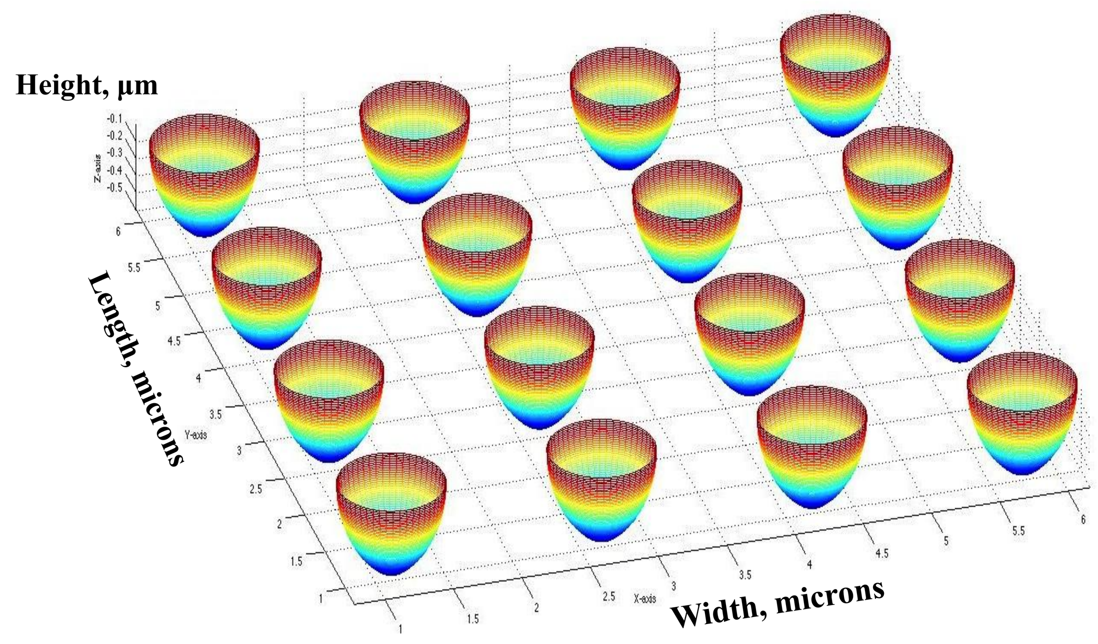

Figure 2. A simulated panel consisting of N=16 Winston cones spaced evenly in a regular pattern.

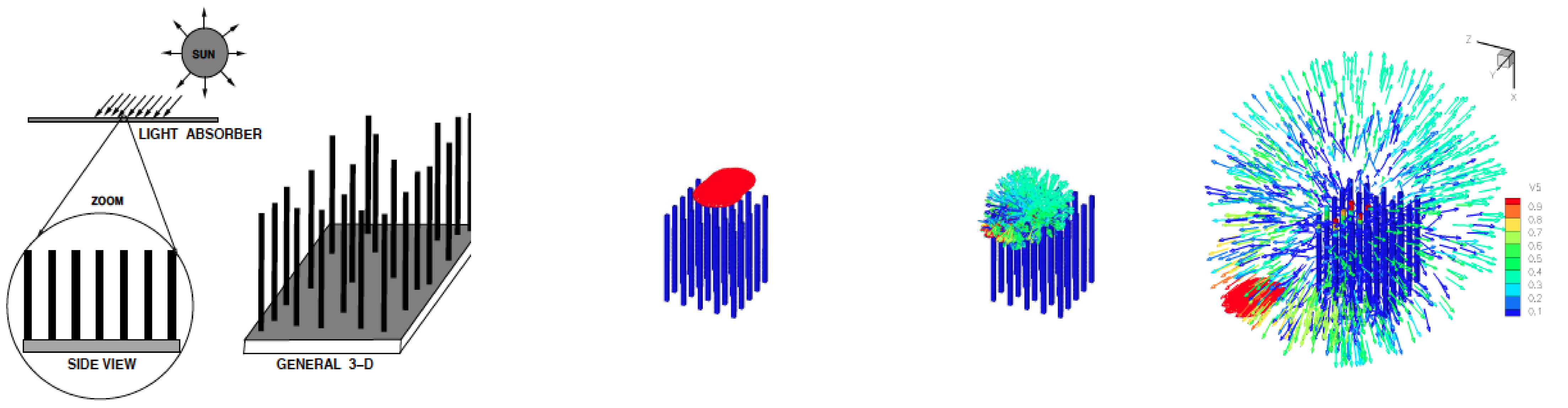

Figure 3. Micro-structural rods and progressive movement of light rays through them (colors of vectors indicate irradiance; colors of rods indicate absorption of irradiant energy; overall reflectivity is dictated by the orientation and the coatings of the rods).

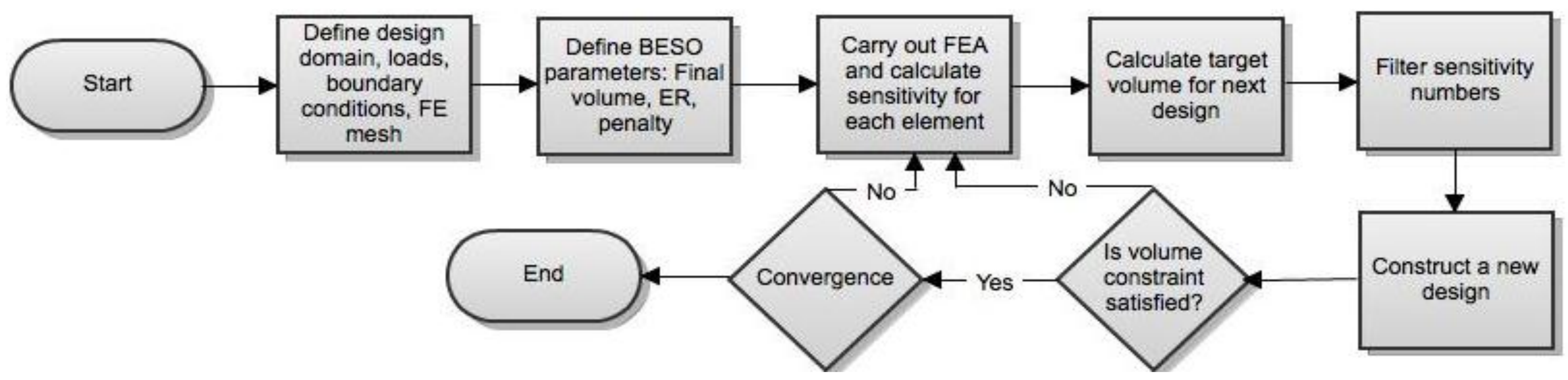

Figure 4. Flow chart describing the Bi-directional Evolutionary Structural Optimization (BESO) method.

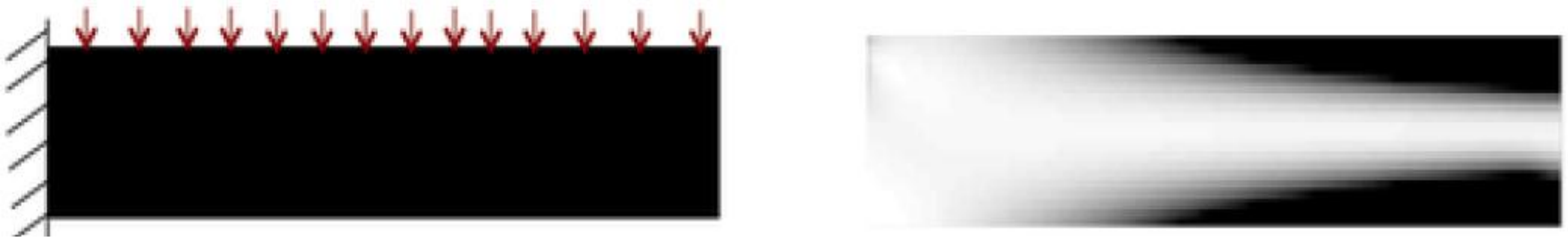

Figure 5. Uniform loading conditions of one Newton applied to the cantilever beam fixed at the left end (left) and optimal design obtained for the beam after performing BESO (right) where 40% of total material is removed from the final topology. The gray region represents the final geometry for the cantilever beam under the stated loading conditions while the black regions correspond to the removed material.

Algorithm for Ray-Tracing

- Start with N light rays positioned just above the panel. At any time, we track the progression of N photons contained within our N rays.
- If a ray encounters surface:
  - For a surface $\Phi(x_1, x_2, x_3) = 0$ compute intersection
  - Compute normal: $n = \nabla\Phi(x_1,x_2,x_3)/\|\nabla\Phi(x_1,x_2,x_3)\|$
  - Compute reflected ray relative to the normal ray (in plane)
  - Compute angle change for the reflected ray
- March all the photons by one time step Δt,

<u>For a Winston cone panel</u>:
  - Rays within an acceptance angle of cone are accepted while the rest are rejected.
  - Rays entering from the top undergo total internal reflections within the cone and exit from the bottom.

<u>For a panel containing micro-array rods</u>:
  - Rays hitting the top and sides of micro-array rods undergo trajectory change using Fresnel conditions.
  - Absorption by rods, i.e. ray magnitude change, is

$$R = \frac{1}{2}\left(\left(\frac{\frac{\hat{n}^2}{\mu}\cos\theta_i - \sqrt{(\hat{n}^2 - \sin^2\theta_i)}}{\frac{\hat{n}^2}{\mu}\cos\theta_i + \sqrt{(\hat{n}^2 - \sin^2\theta_i)}}\right)^2 + \left(\frac{\cos\theta_i - \frac{1}{\mu}\sqrt{(\hat{n}^2 - \sin^2\theta_i)}}{\cos\theta_i + \frac{1}{\mu}\sqrt{(\hat{n}^2 - \sin^2\theta_i)}}\right)^2\right)$$

where R represents the reflectivity factor,
$\hat{n}$ is the relative dielectric constant of the refracting medium,
μ is permeability with respect to free space, and
θ_i is the angle of incidence for light.

- Increment all ray front positions (ray velocity = v):

$$r_i(t+\Delta t) = r_i(t) + \Delta t\, v_i(t)$$

References

1) Zohdi, T.I. "Modeling and simulation of the optical response of rod-functionalized reflective surfaces." *Computational Mechanics* (2012): 1-12.
2) Huang, X., Xi, Y.M., and Burry, M.C. "A new algorithm for bi-directional evolutionary structural optimization." *JSME International Journal Series C* 49.4 (2006): 1091-1099.
3) Winston, R., Miñano, J.C., and Benitez, P.G. *Nonimaging optics*. Academic Press, 2004.

Concluding Remarks

The poster introduces different ways in which a building façade can be modified to capture and harness photovoltaic energy for various purposes, including providing natural light conditions in a building. Geometrical ray-tracing is extensively used to track the movement of these rays once they are captured by the features on the façade. Moreover, with a substantial rise in the availability of computational power, the implementation and analysis of these models have become highly tractable. Since light rays travel independently of one another, we can highly parallelize the problem: (1) By assigning each processor its share of rays, and checking which features interact with those rays, or (2) By assigning each processor its share of features, and checking which rays interact with them.