Optimal Sensor Placement in 3D Architectural CAD

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MOTIVATION

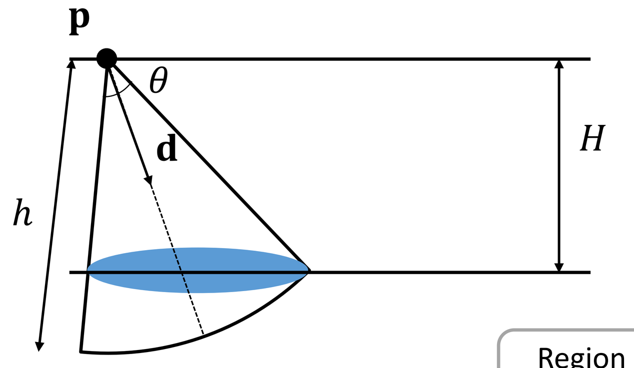
How can we optimally place sensors in 3D architectural CAD environment?

- Extract the region of interests from CAD
- Zone of sensor coverage can either be isotropic (temperature, short-range wifi) or directional (cameras, light sensors, long-range wifi, movement sensors)
- Embrace the visibility or performance interference due to architectural structures
- Consider restrictions on the installation
- Visualize and simulate integrated in BIM software

OBJECTIVE

We place cameras (directional sensors) on the ceilings of building to maximize coverage in Autodesk Revit model.

- $C^{\theta,h}(\mathbf{p}, \mathbf{d})$: Conic camera coverage placed at **p**, directed toward **d**, maximum range h, field of view θ



- Ψ: coverage to maximize

Region not occluded by model M from p

$$\Psi = \left[\cup_{i=1,\cdots,n}\{C^{\theta,h}(\mathbf{p}_i,\mathbf{d}_i)\cap\Gamma^{\mathcal{M}}(\mathbf{p}_i)\}\right]\cap V^{\mathcal{G}}(0,H).$$

Volume enclosed by polygon G between floor (0) and ceiling (H)

CONTRIBUTION

- We present an approximating approach to solve NP-hard geometric optimization problem into two-stage problem

Partition the domain of coverage
Consider geometric constraints

→

Find optimal location of sensors
Consider the partition and local neighborhood

- We integrate the input and output of sensor placement and coverage problem with BIM [1] framework.
- We demonstrate that the Voronoi-based neighborhood evaluation can provide a sub-optimal way to optimize for non-spherical coverage, and definitely better than the widely-used greedy approach.

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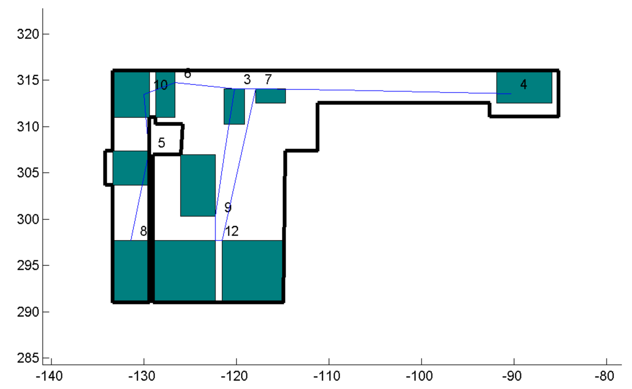
TWO-STAGE APPROACH

Stage 1: Partition of the query region using 2D disks

- Create regular placement of sensors within the defined region to find configuration of sensor locations
- We use disk of radius r centered at **q**, $b^r(\mathbf{q})$, to cover the 2D polygonal region

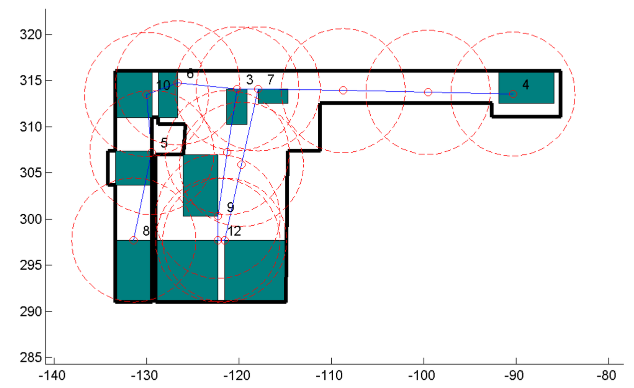
$$\hat{\Psi} = \left[\cup_{i=1,\cdots,n}\{b^r(\mathbf{q}_i)\cap\Gamma^{\mathcal{M}}(\mathbf{p}_i)\}\right]\cap P^{\mathcal{G}}(0).$$

- The goal is to find a configuration that neighboring disks to touch



Boundary condition

Guarantee coverage of vertices within distance of r and merging overlapping constraints. Connect vertices with edges.

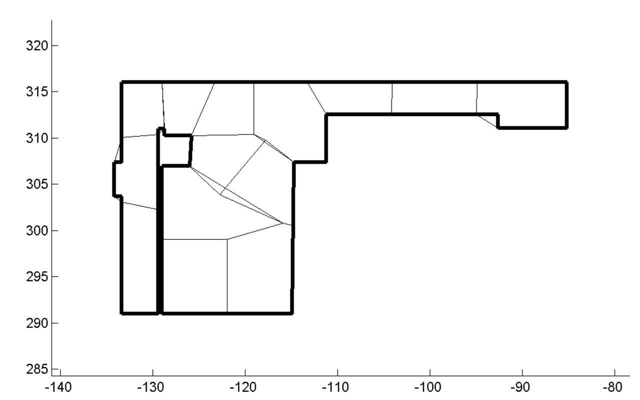


Disk placement

Run CVT [2] to find regular placement for interior region.

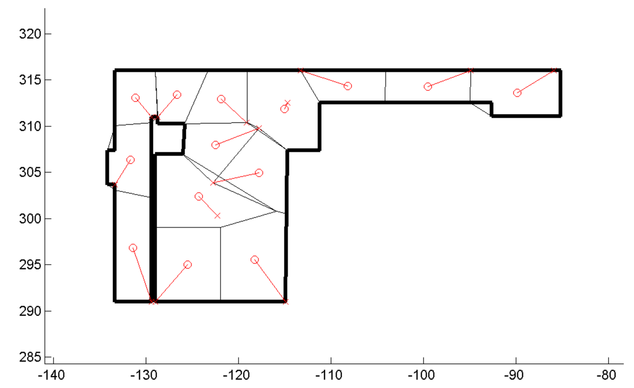
Add additional disk if distance is larger than 2r.

Stage 2: Optimize sensor placement given configuration



Voronoi partition

Given the approximate arrangement of disks, extract a Voronoi partition and neighborhood information.



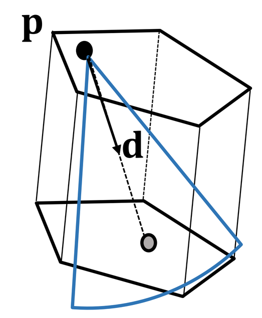
Sensor placement

Place one sensor within one Voronoi cell whose apex is inside ceiling projection of Voronoi cell and pointing toward the center of the cell on the floor.

$$|\Psi| \cong \sum_{i=1,\cdots,n}\Big\{f(\mathbf{p}_i,\mathbf{c}_i)+\sum_{j\in N(i)} g(\mathbf{p}_j,\mathbf{p}_i,\mathbf{c}_i)\Big\}.$$

Cone coverage by cone in the same cell

Additional coverage by the neighboring cone



Choose apex position among vertices based on optimization

$$\begin{aligned}\underset{X}{\text{maximize}}\quad & X^TWX\\ \text{subject to}\quad & \mathbf{x}_i\geq 0,\ i=1,\cdots,n,\\ & \mathbf{x}_i^T\mathbf{1}=1,\ i=1,\cdots,n.\end{aligned}$$

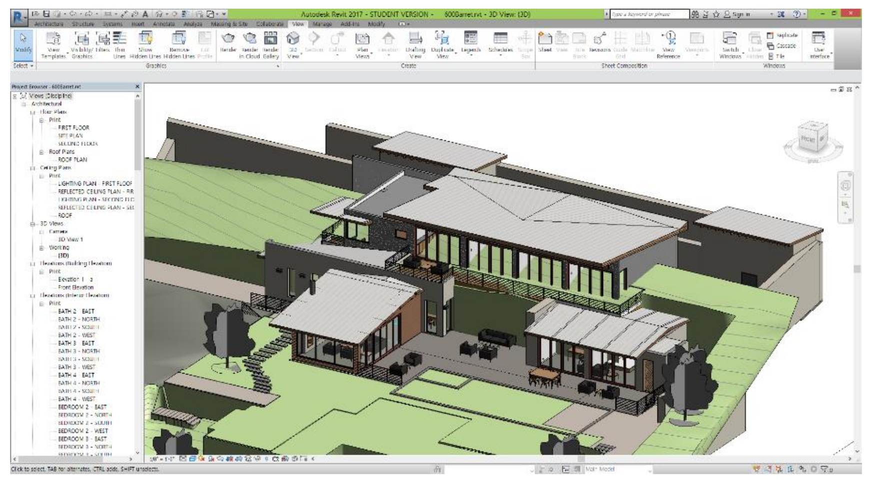
⇨ SDP relaxation

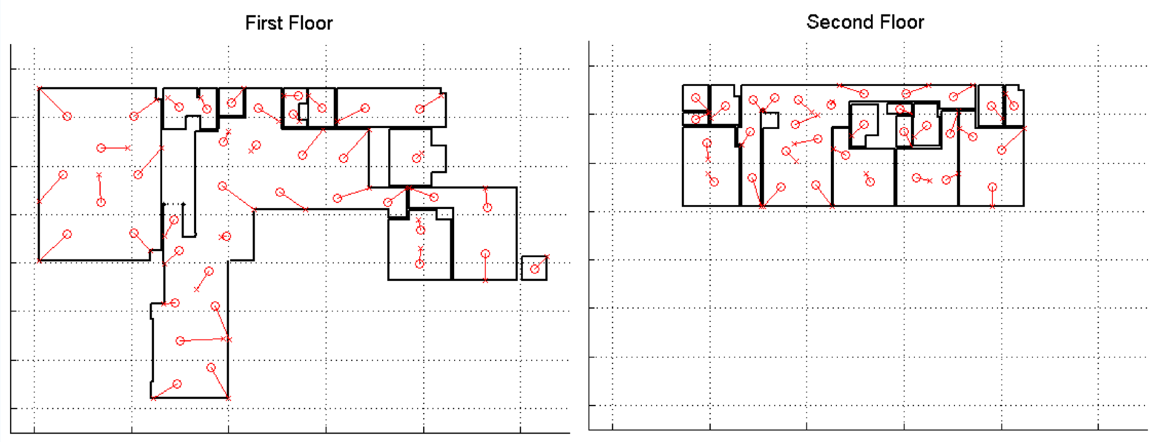
$$\begin{aligned}\underset{X,Y}{\text{maximize}}\quad & \mathrm{tr}(WY)\\ \text{subject to}\quad & Y\succeq XX^T,\\ & \mathrm{tr}Y=n,\\ & \mathbf{x}_i\geq 0,\ i=1,\cdots,n,\\ & \mathbf{x}_i^T\mathbf{1}=1,\ i=1,\cdots,n.\end{aligned}$$

RESULTS

Results with a complete house

We tested our algorithm to place cameras into a 51MB Revit model of a two-story house with 32 rooms spanning 4791 ft^2. Our results cover about 67.2% of the interior volume using 74 cameras.



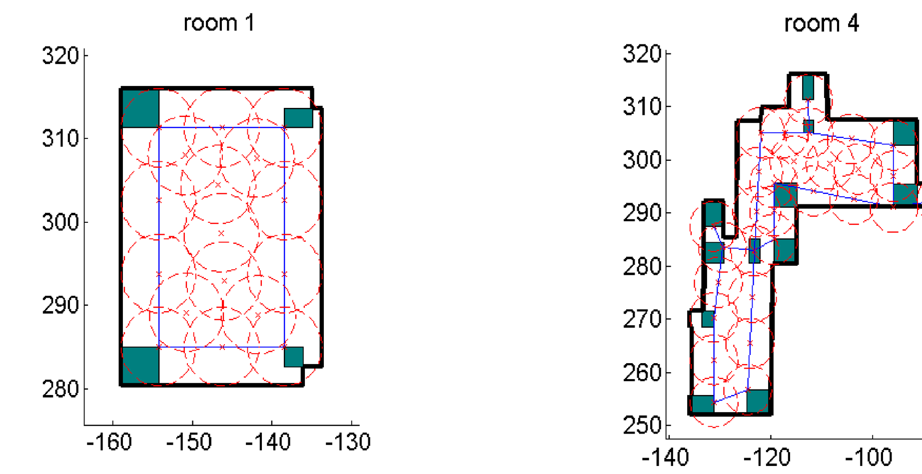


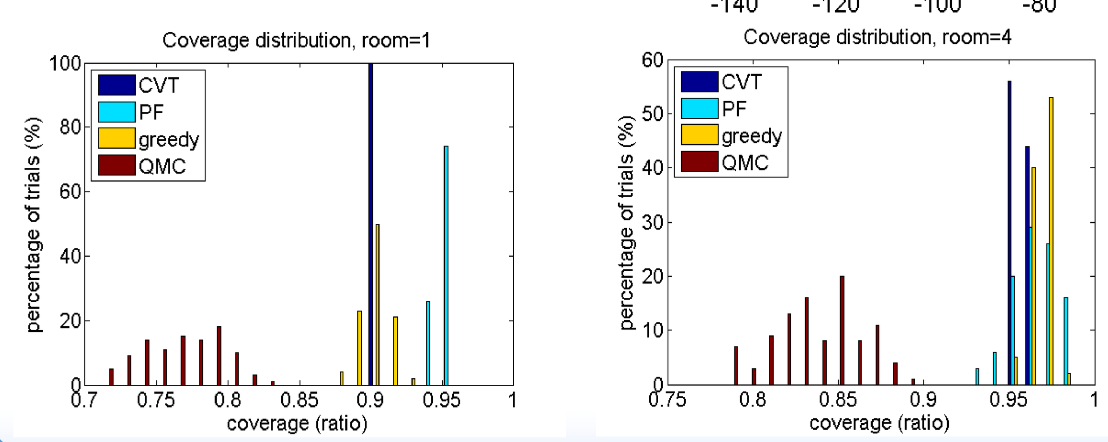
Comparison of disk placement (stage 1)

Even 2D disk coverage of arbitrary polygonal region is NP-hard problem [3] and we compare the performance of our disk placement (CVT) with other commonly used approaches of greedy solution [4,5] (implemented using submodular optimization [6]), potential-field based method (PF) [7,8], and low-discrepancy Quasi-Monte Carlo sampling with Sobol sequence (QMC) [9,10].

- PF works the best, and performs well in open space (room1). PF suffers from local minima.
- Greedy algorithm performs better under complex geometric constraints, and not significant under open space.
- QMC algorithm is a quick way to placing low-discrepancy points, but it is not very reliable especially with complex boundary conditions.
- While CVT is not the best in terms of coverage, it is fast and stable.

		CVT	PF	greedy	QMC
room1	coverage	0.909	0.950	0.903	0.766
	time (s)	0.028	1.974	110.036	0.132
room4	coverage	0.958	0.965	0.968	0.837
	time (s)	0.045	10.381	197.408	0.474



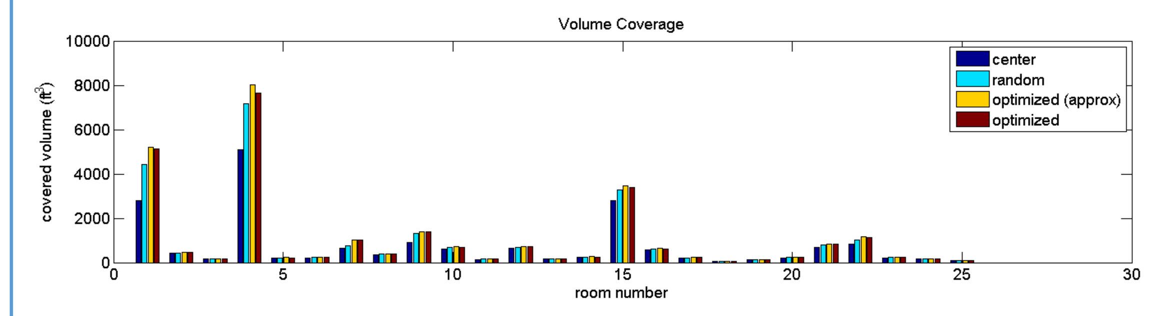


RESULTS (cont.)

Comparison of apex placement (stage 2)

We compare our optimized position using SDP formulation with center placement pointing straight down and the random placement on the Voronoi vertices. Placing apex at the center covers roughly 48.1% of the volume, which improved to 62.0% by tilting the apex to one of the vertices. After further optimization, the coverage is further increased to 67.2%. Our approximate coverage value of the optimization objective overshoot the actual coverage by about 1.7% of total volume.

Apex at the center	48.1 %
Apex at random Voronoi vertex	62.0 %
Approximated coverage (SDP)	68.9 %
Optimized apex (SDP)	67.2 %



CONCLUSIONS

We presented the problem of placing cameras in architectural environment with realistic models. The necessary information of the suggested algorithm can be extracted with widely used BIM software. Based on the parameters, we can optimally place sensors by first finding the neighborhood arrangement with disk approximation and optimize for the best coverage under the configuration. Even though the current optimization considers only pairwise interaction between neighboring sensors, the optimized coverage is within 1-2% error. More importantly, our partition simplifies the complex geometry and visibility problems. To the best of our knowledge, we are the first to define and suggest a complete pipeline to optimize the camera coverage under complex architectural environment integrated with the software that is commonly used in the architectural field.

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ACKNOWLEDGEMENTS

This research was supported in part by a grants from NIH (R01-GM117594), NIH (R41-GM116300) and the Seton-DELL medical school.