Piecewise-Planar 3D Reconstruction with Edge and Corner Regularization

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Need

3D models of existing buildings:

- thermal or acoustic simulations
- light and shadow casting
- Building Information Models

Existing solutions

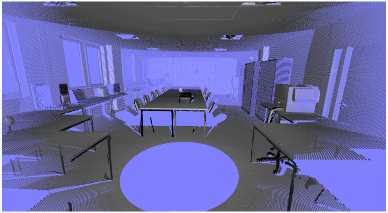
Laser point clouds + semi-automatic surface reconstruction

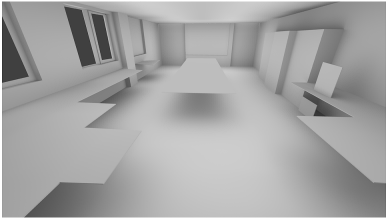
- error prone
- time consuming
- expensive

Objective

Automatic 3D surface reconstruction from point cloud

- watertight without self-intersection
- extends in a plausible manner in hidden regions
- piecewise planar

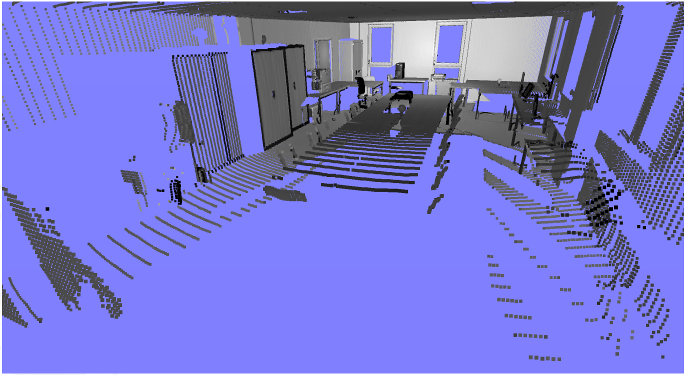




Challenges

Two main challenges

- ubiquitous occlusions
- sampling anisotropy



Limitation of existing methods

- Smooth surfaces priors are inadequate
- Intersects only pairs of planes that are adjacent in range image
- Manhattan world assumption: too restrictive
- Watertight solutions not guaranteed
- Voxelization: biased, expensive
- Delaunay tetrahedralization: visible regions only

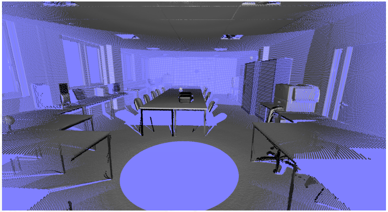
[Chauve 2009]

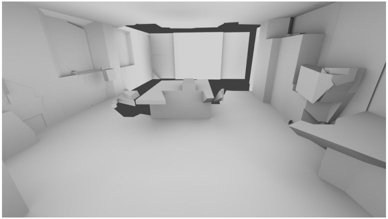
- Plane arrangement
  - Planes detected in the point cloud using region growing
  - Hidden planes hypotheses (ghosts) guessed from the edges of detected polygons
- binary labelization of the 3D space
  - pairwise MRF (2nd order factors)
  - solution with graph-cut
- Advantages
  - watertight solution
  - primitives can expand far beyond their visibility area
  - allows the use of hidden planes hypotheses
  - sharp surface reconstruction

[Chauve et al. 2009]

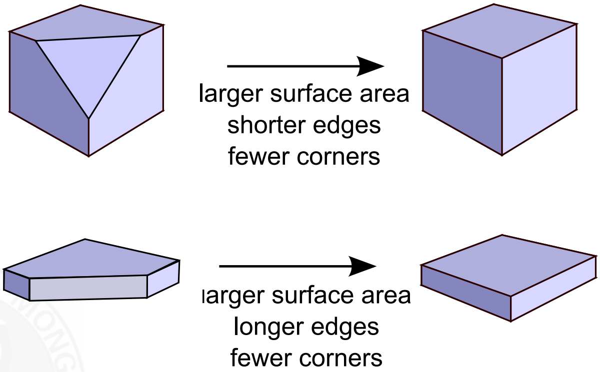
Limitations:

- anisotropy of laser point clouds is a problem
- missing plane hypotheses
- surface area minimization creates holes and cutted corners





Surface area vs Edges length vs Corners count



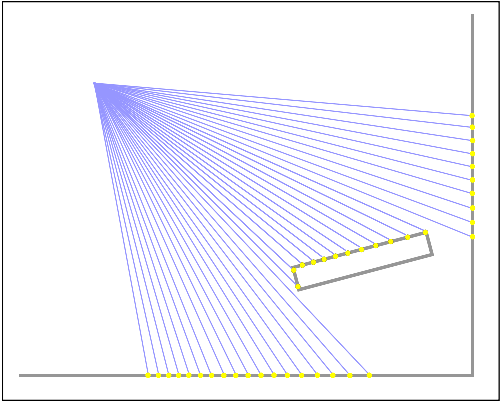
Our approach

Contributions

- treatment of sampling anisotropy
- better and new plane hypotheses
- higher-order regularization:
  - **length of edges** (4th order factors)
  - **number of corners** (8th order factors)
- globally near optimal solutions using LP relaxation

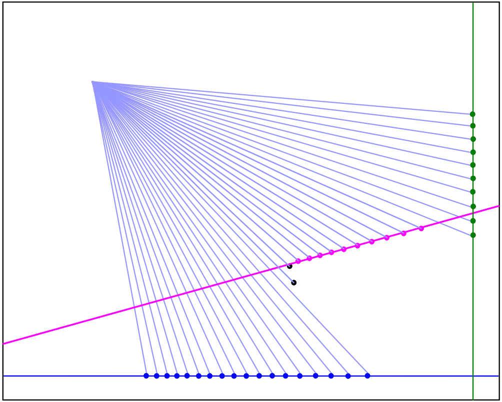
Method overview

- laser measures



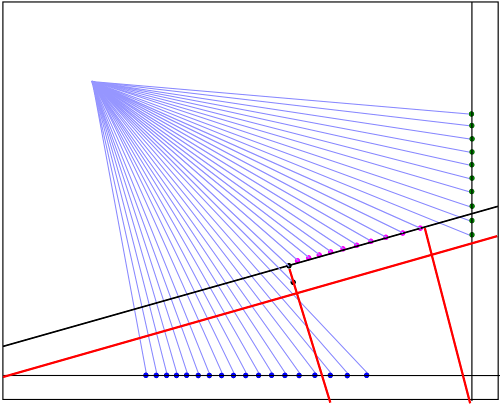
Method overview

- laser measures
- planes detection



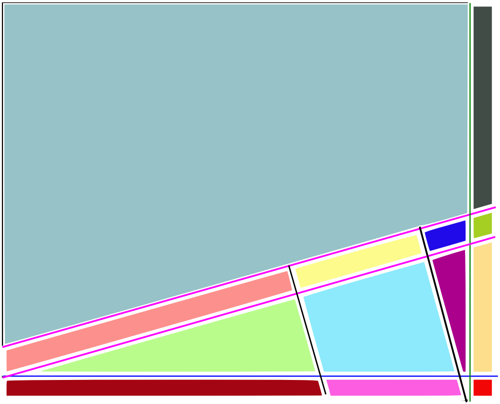
Method overview

- laser measures
- planes detection
- region polygonization and Ghosts creation



Method overview

- laser measures
- planes detection
- region polygonization and Ghosts creation
- volume partition using a plane arrangement



Method overview

- laser measures
- planes detection
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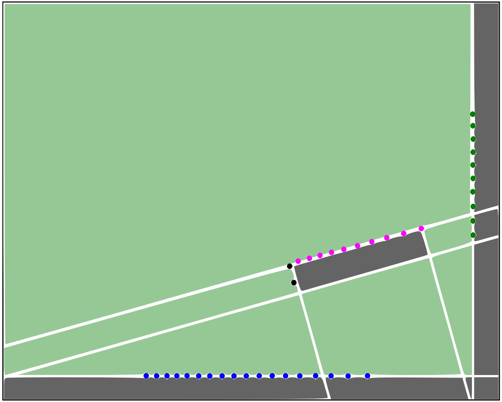
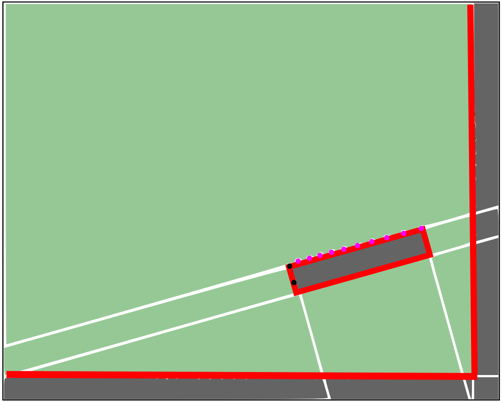
- LP Binary labelization



Method overview

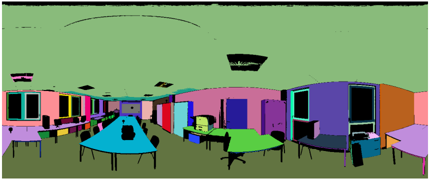
- laser measures
- planes detection
- region polygonization and Ghosts creation
- volume partition using a plane arrangement
- LP Binary labelization
- surface extraction



Plan detection

Region growing approach.

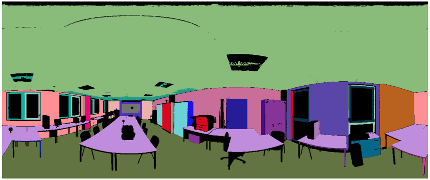
- compute point normals with a method that preserves sharp features [Boulch et al. 2012]
- locally planar region as seeds
- grow region from seeds
- keep plane equations updated using online least-square fitting



Plan detection

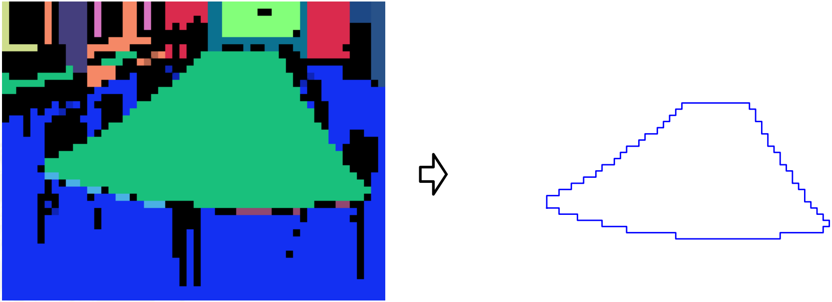
plane fusion to recover from over-segmentation using robust statistical criteria [Boulch et al. 2014]

⇓



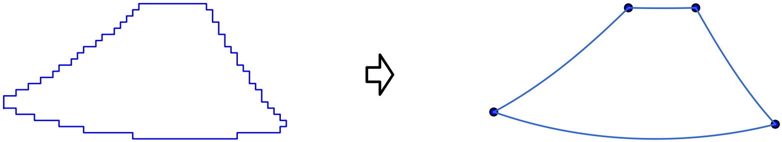
Polygonization

- Extraction of the the boundary pixel chain

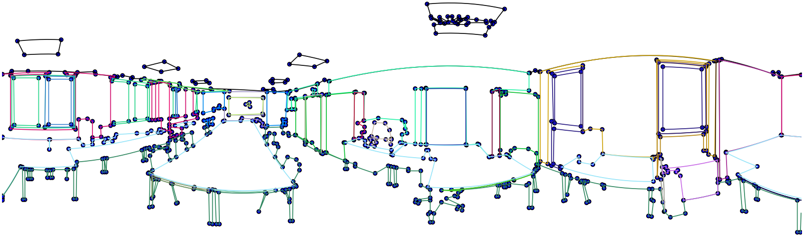


Polygonization

- Extraction of the the boundary pixel chain
- Polygon simplification by greedy merging of adjacent edges, keeping maximum distance to the original polygon below 2 pixels (aliasing)

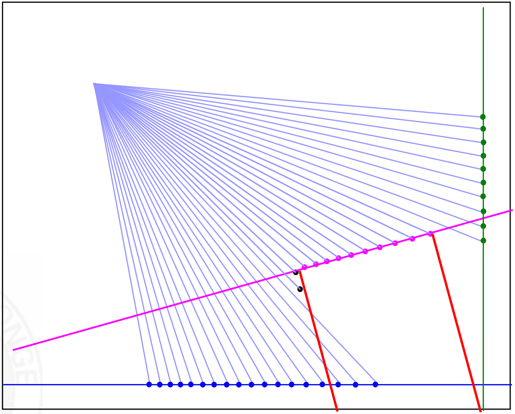


Polygonization

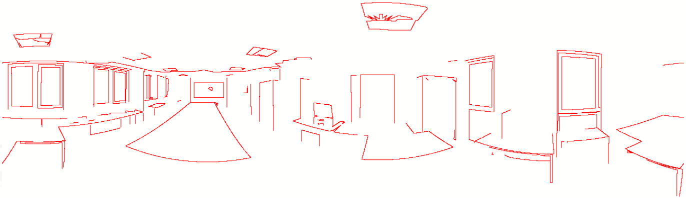


Orthogonal ghosts

We generate an orthogonal half-plane for each polygon edge



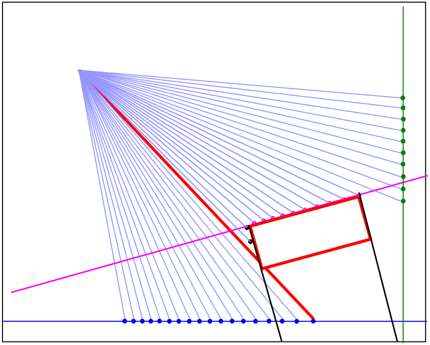
Orthogonal ghosts



Parallel ghosts

thin objects (tables, screens etc.)

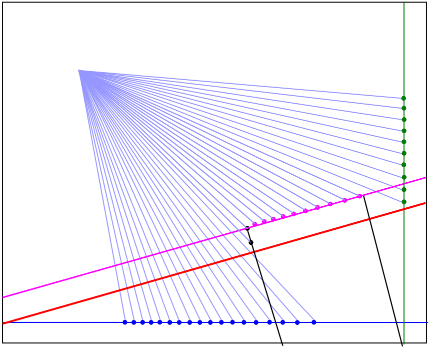
- not enough points on the side
- find largest valid thickness



Parallel ghosts

thin objects (tables, screens etc.)

- not enough points on the side
- find largest valid thickness
- create parallel ghost

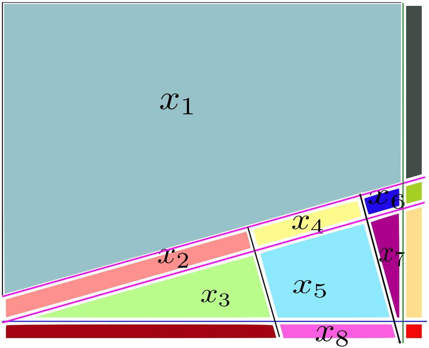


Surface reconstruction

Once we have all the plane candidates ,

- partition the volume with a plane arrangement
- label each cell as empty or full

$$x = (x_1, \ldots, x_N) \in \{0, 1\}^N$$



Surface reconstruction

$$E(x) = E_{data}(x) + E_{regul}(x)$$

labelization through minimization of a sum of terms

- data terms

$$E_{data}(x) = E_{prim}(x) + E_{vis}(x)$$

- the regularization terms

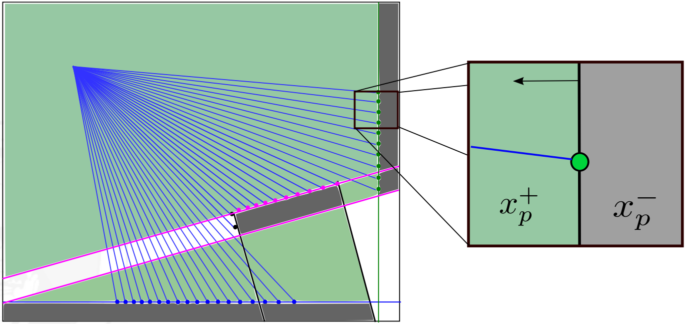
$$E_{\text{regul}}(\mathbf{x}) = E_{\text{area}}(\mathbf{x}) + E_{\text{edge}}(\mathbf{x}) + E_{\text{corner}}(\mathbf{x})$$

  - allows to cope with noisy measurement
  - allows completion in hidden regions

Data term

- cells in front of labeled points should be empty
- cells just behind the points should be full

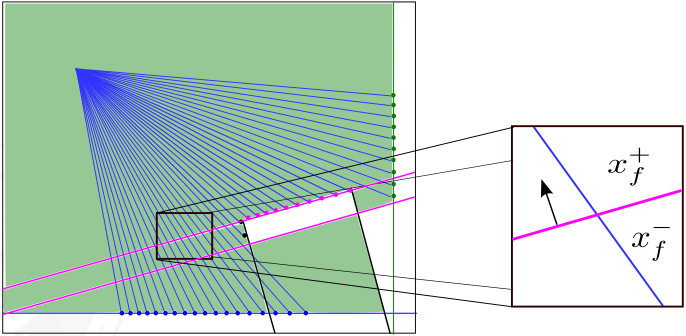
$$E_{\text{prim}}(\mathbf{x}) = \sum_{p \in \mathcal{P}} w_p^{\text{aniso}} \left(x_p^+ + (1 - x_p^-) \right) \tag{1}$$



Data term

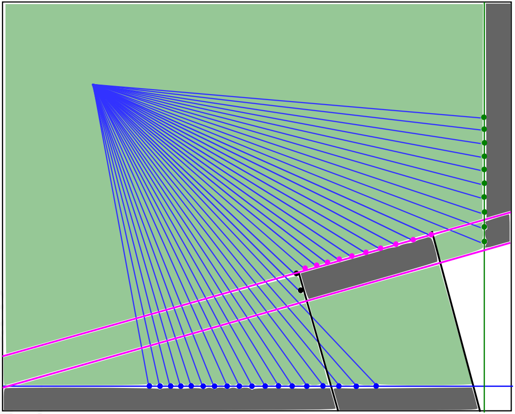
Facets on the surface should not intersect rays

$$E_{\text{vis}}(\mathbf{x}) = \sum_{\substack{p \in \mathcal{P},\ f \in \mathcal{F} \\ \omega p \cap f \neq \emptyset}} w_p^{\text{aniso}} \left| x_{f^+} - x_{f^-} \right| \tag{2}$$



Data term

Data term are not enough to label all cells



Surface area regularization

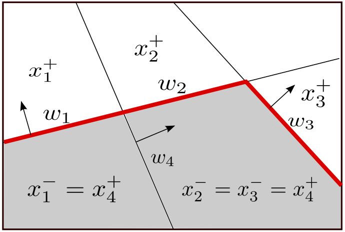
- the total area of the surface is

$$E_{\text{area}}(\mathbf{x}) = \sum_{f \in \mathcal{F}} w_f \, |x_{f^+} - x_{f^-}| \tag{3}$$

with

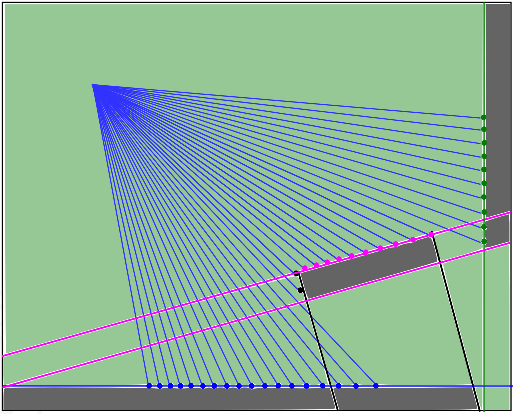
$$w_f = a_f / \sigma^2$$

where σ is a scale parameter and a_f the area of the facet



Data term + Area term

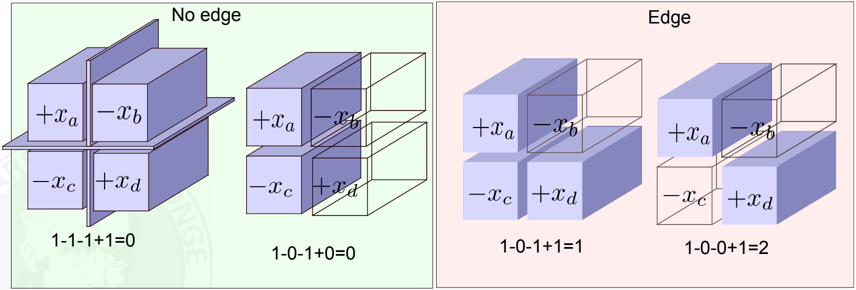
Area term does not fill large gaps



Edge length regularization

existence of an edge as a linear function of the adjacent cell binary values:

$$h_e(x) = x_a - x_b - x_c + x_d$$



Edge length regularization

The total edge length of the surface is penalized in the optimized energy using

$$E_{\text{edge}}(\mathsf{x}) = \sum_{e \in \mathcal{E}} w_e \left| h_e(\mathsf{x}) \right| \tag{4}$$

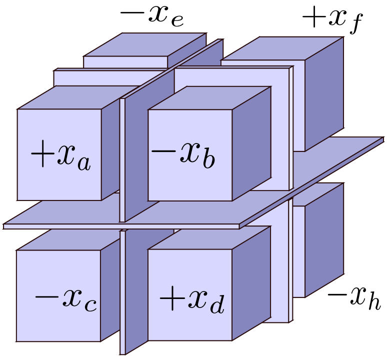
With

$$w_e = \frac{l_e}{\sigma} \; w_{\text{ang}}(\alpha_e) \tag{5}$$

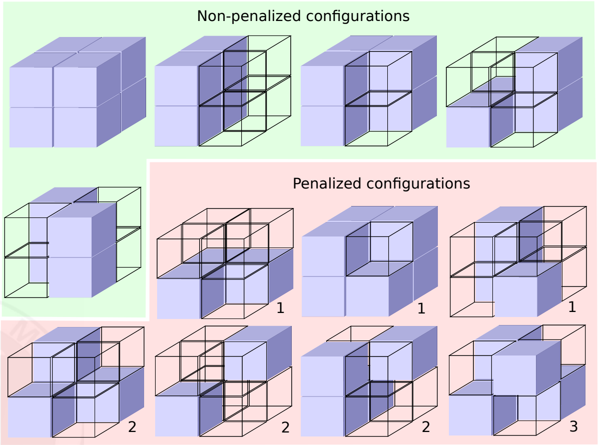
with σ the scale parameter and $w_{\text{ang}}(\alpha_e)$ a function of the angle between the two planes

Corners count regularization

$$h_v(x) = x_a - x_b - x_c + x_d - x_e + x_f + x_g - x_h$$



Corners count regularization



Corners count regularization

We penalize the number of corner in the reconstructed surface by adding to he minimized energy the term

$$E_{\text{corner}}(\mathsf{x}) = \sum_{v \in \mathcal{V}} w_v \left| h_v(\mathsf{x}) \right| \tag{6}$$

W_v depends on the three angles between each pair of plane:

$$w_v = w_{\text{ang}}(\alpha_1, \alpha_2, \alpha_3) \tag{7}$$

The corner count terms correspond to potentials of order up to 8 in the context of MRFs

Optimization

- 8th order potential are challenging for MRF minimization methods.
  - Tree-reweighted Belief Propagation, extremely slow to converge
  - Lazy Flipper : local minimum, extremely suboptimal
- We formulate the labeling problem as a Mixed-integer programming problem

Optimization

The total minimized energy can be written as

$$E(x) = \zeta + \sum_i w_i |H_i \,.\, x|$$

with ζ a constant and each H_i is a sparse vector
using an auxiliary variable y_i, each term can be formulated as linear term with additional constraints

$$w_i |H_i \,.\, x| = \min_{y_i} w_i y_i \quad s.t. \quad -y_i \leq H_i \,.\, x \leq y_i \tag{8}$$

thus we aim to solve the integer program

$$min_{x,y} \sum_i w_i y_i \quad s.t. \;\; x \in \{0,1\}^N, \forall i : -y_i \leq H_i \,.\, x \leq y_i \tag{9}$$

Optimization

we aim to solve the integer program

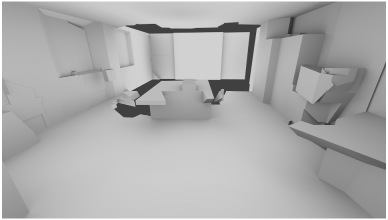
$$min_{x,y} \sum_i w_i y_i \quad s.t. \;\; x \in \{0,1\}^N, \forall i : -y_i \leq H_i \,.\, x \leq y_i \qquad (10)$$

we relaxe the integer constraint $x \in \{0,1\}^N$ to the box constraint $x \in [0,1]^N$:

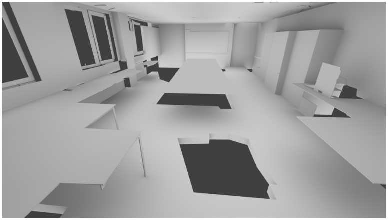
$$min_{x,y} \sum_i w_i y_i \quad s.t. \;\; x \in [0,1]^N, \forall i : -y_i \leq H_i \,.\, x \leq y_i \qquad (11)$$

This is a standard Linear Program, We solve it using the dual simplex in the commercial Mosek© solver. After rounding to solution to integers we obtained an increase of energy not greater than 8%.

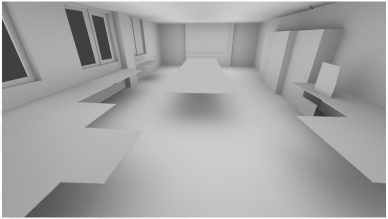
Results



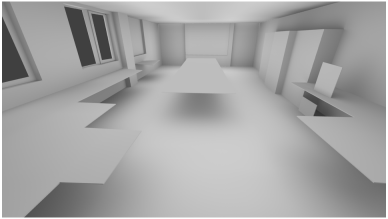
chauve & al



surface only

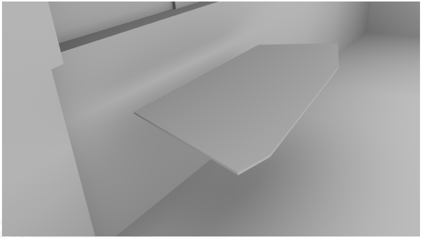


edges only

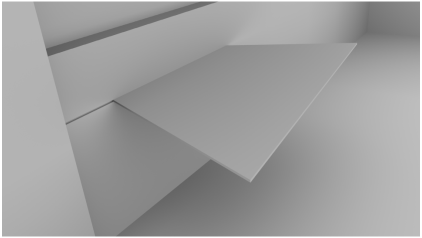


corners only

Results



edges



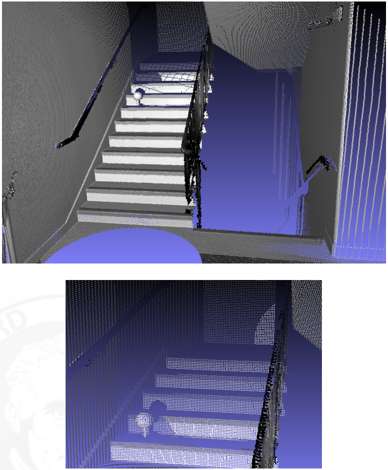
corners

Results

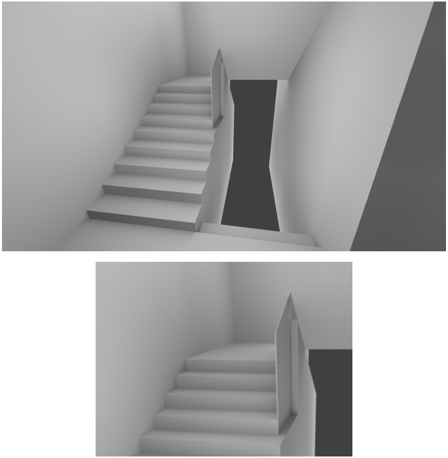
corners

edge+corners

Results



point cloud



reconstruction

Conclusion

- allows plausible completion in hidden regions
- handles anisotropy
- edge and corner regularization superior to area term for completion
- near-optimal global solution using efficient LP relaxation

Futur work

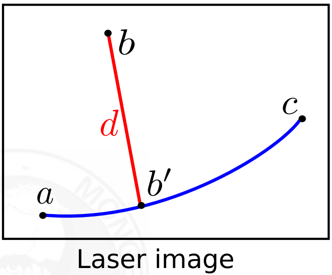
- photogrammetry
- better scalability to large scenes

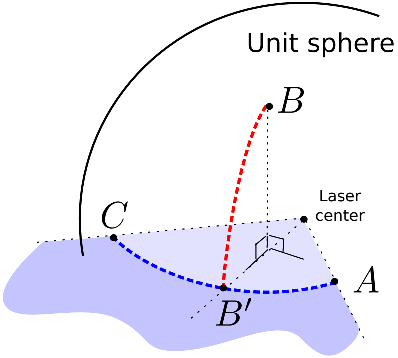
Links

- This work was partly supported by Bouygues Construction interested in automatic BIM generation from existing buildings
- emails:
  - martin.de-la-gorce@enpc.fr
  - alexandre.boulch@enpc.fr
  - renaud.marlet@enpc.fr
- IMAGINE team website:
  - imagine.enpc.fr

Polygonization

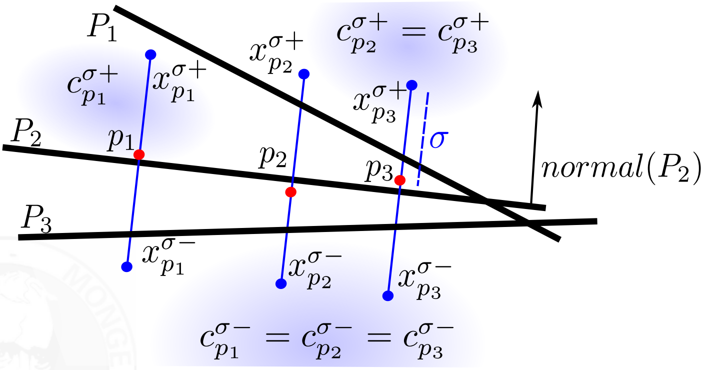
The polygones have curvy edges in the image coordinate system. we compute the distance of a point to a curvy segment using geodesqic projection in the the sphere





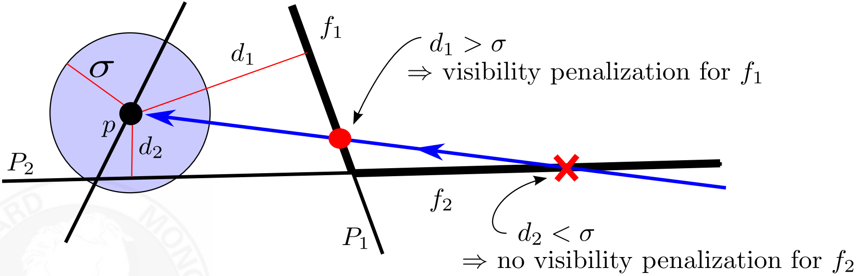
Data term

The surface should pass near observed points:



Data term

The surface should not intersect any segment joining the scanner center and the observed points



Data term

- We penalize full cell just in front of a point and empty cell just behind a point

$$E_{\text{prim}}(\mathsf{x}) = \sum_{p \in \mathcal{P}} w_p^{\text{aniso}}(P_p) \left(x_p^{\sigma+} + (1 - x_p^{\sigma-}) \right) \tag{12}$$

- We use a penalization weight that take anisotropy into account

$$w_p^{\text{aniso}}(P) = \frac{d^2}{\sigma^2} \Delta_\theta \Delta_\phi \frac{\sin\phi}{\cos\psi} \tag{13}$$

with θ the azimuth angle, ϕ the polar angle , Δ_θ and Δ_ϕ the two steps of the scan.

Data term

We penalize the use of facets that intersect the segments joining the laser center and the observed points

$$E_{\text{vis}}(\mathbf{x}) = \sum_{\substack{p \in \mathcal{P},\ f \in \mathcal{F} \\ \omega p \cap f \neq \emptyset,\ d(p, P_f) \leq \sigma}} w_p^{\text{aniso}}(P_f)\,|x_{f^+} - x_{f^-}| \qquad (14)$$

Corners count regularization

We penalize the number of corner in the reconstructed surface by adding to he minimized energy the term

$$E_{\text{corner}}(\mathsf{x}) = \sum_{v \in \mathcal{V}} w_v \left| h_v(\mathsf{x}) \right| \quad (15)$$

W_v depends on the three angles between each pair of plane:

$$w_v = w_{\text{ang}}(\alpha_1, \alpha_2, \alpha_3) = A + (1 - A) \exp\left(-\frac{\sum_{i \in \{1,2,3\}} (\alpha_i - \pi/2)^2}{2\rho^2}\right) \quad (16)$$

The corner count terms correspond to potentials of order up to 8 in the context of MRFs