Optimized Positioning of Autonomous Surgical Lamps

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Motivation

Introduction

- *“Indicating shortcomings in surgical lighting systems”*, Knulst et al., 2011
  - Manual adjustments on average every 7 minutes
  - Up to 30 seconds
- Manual adjustments are
  - Physically straining
  - Time consuming
  - Interrupting the workflow
  - Contributing to high cognitive load
- Leads to working under sub-optimal lighting conditions

Previous Work

Patents:

- *“General purpose distributed operating room control system”*, Wang et al., 2003
- *“Automated surgical illumination system”*, G. M. Kim and T. L. Chen, 2012

Papers:

- *“Optimal C-arm Positioning for Aortic Interventions”*, Virga et al., 2015

Our Goal: truly autonomous surgical lamps

- Multi-objective optimization (MOO) problem
  - Maximize uniform lighting
  - Minimize occlusion
  - Minimize movement

  → Conflicting optimization goal
- MOO usually needs validation of results
- Can‘t ask surgeons about their preferences during intervention
  - Scalarized MOO (weighted sum)
- But we can ask at the start

  → meta-optimization

Contributions

1. New optimization scheme at runtime
   - Leads to longer stretches of no movement
2. Meta-optimization to optimize weights
   - Yields Pareto-front of optimal solutions
3. Easy-to-understand metrics
   - Easy to pick use-case-dependent set of weights

Autonomous Surgical Lamps – Setup

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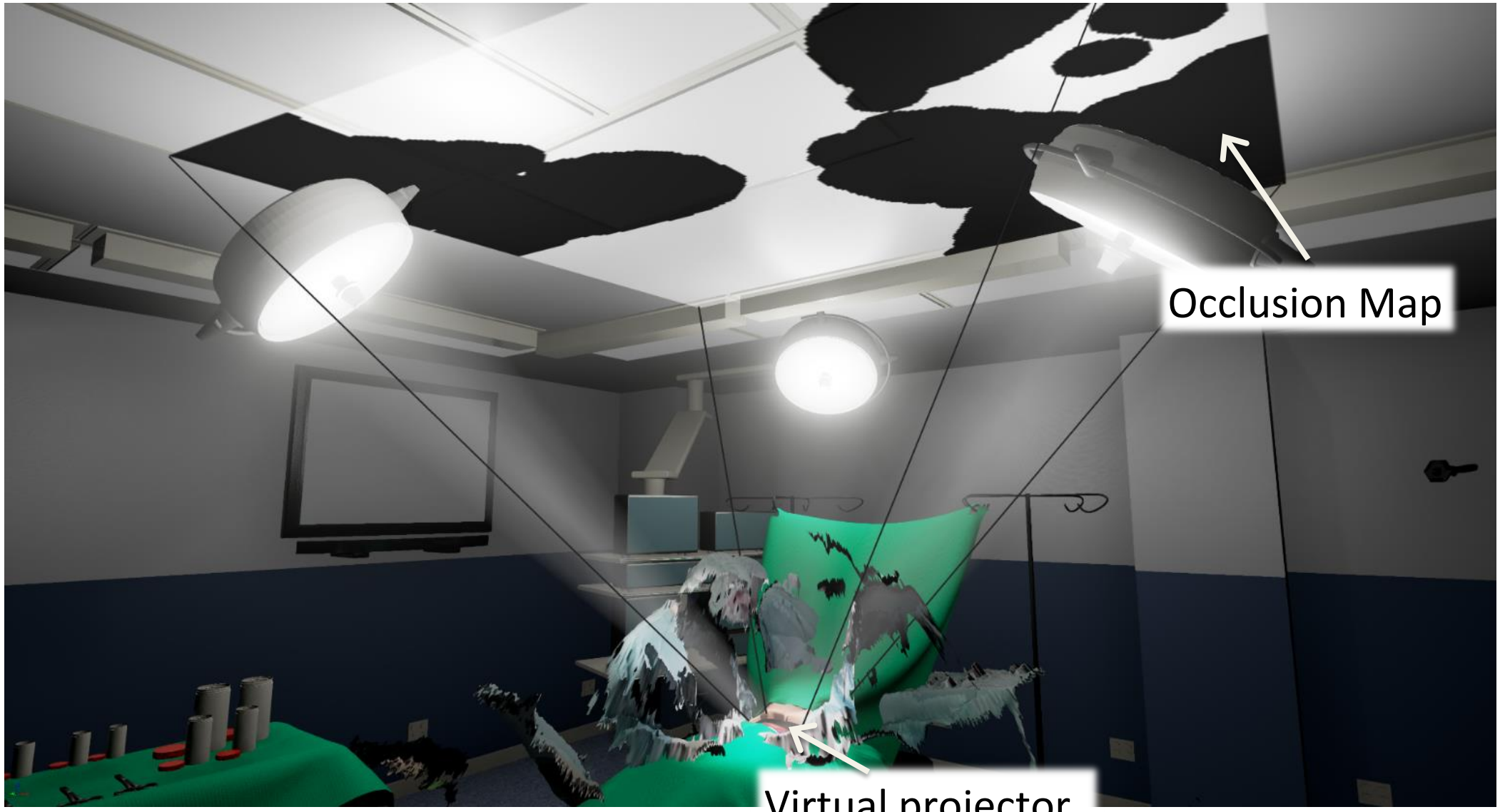
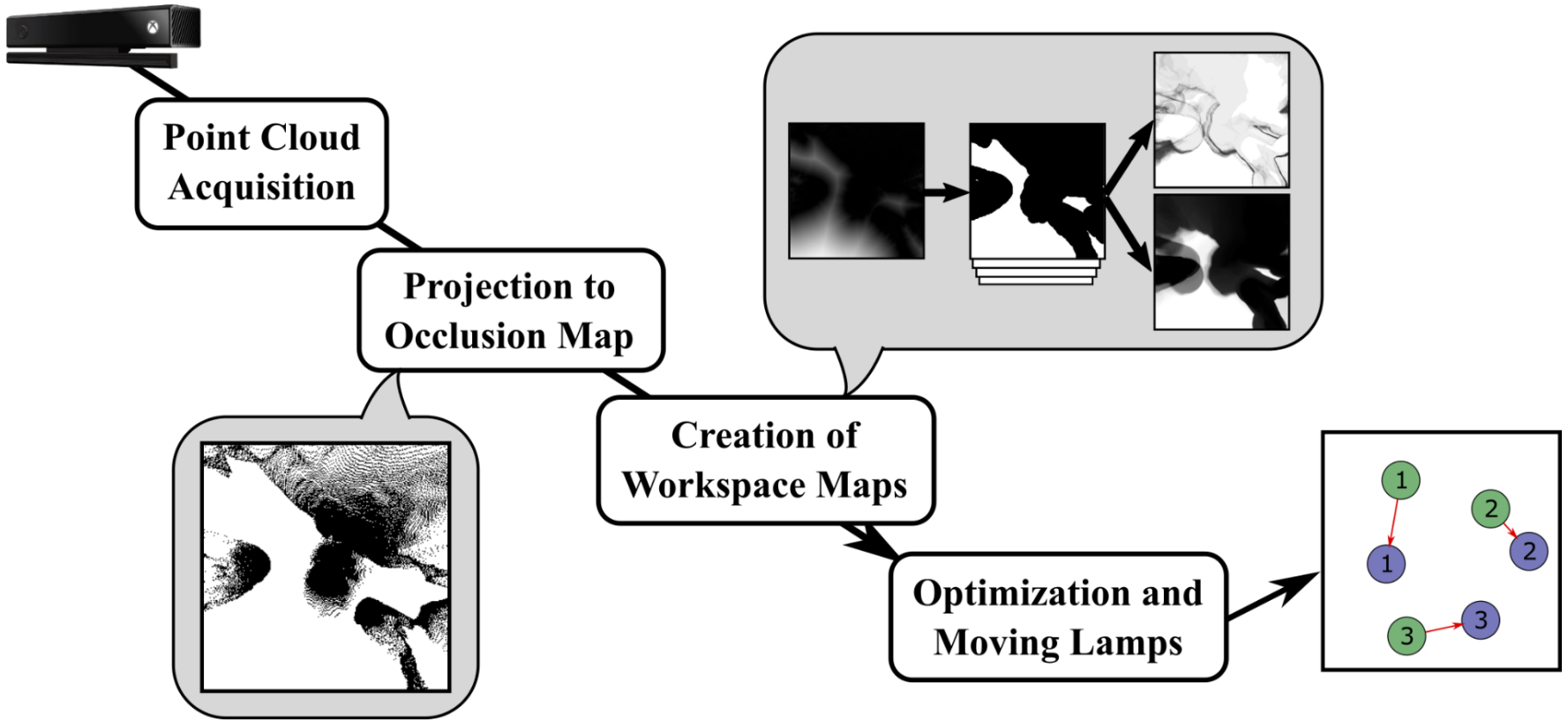
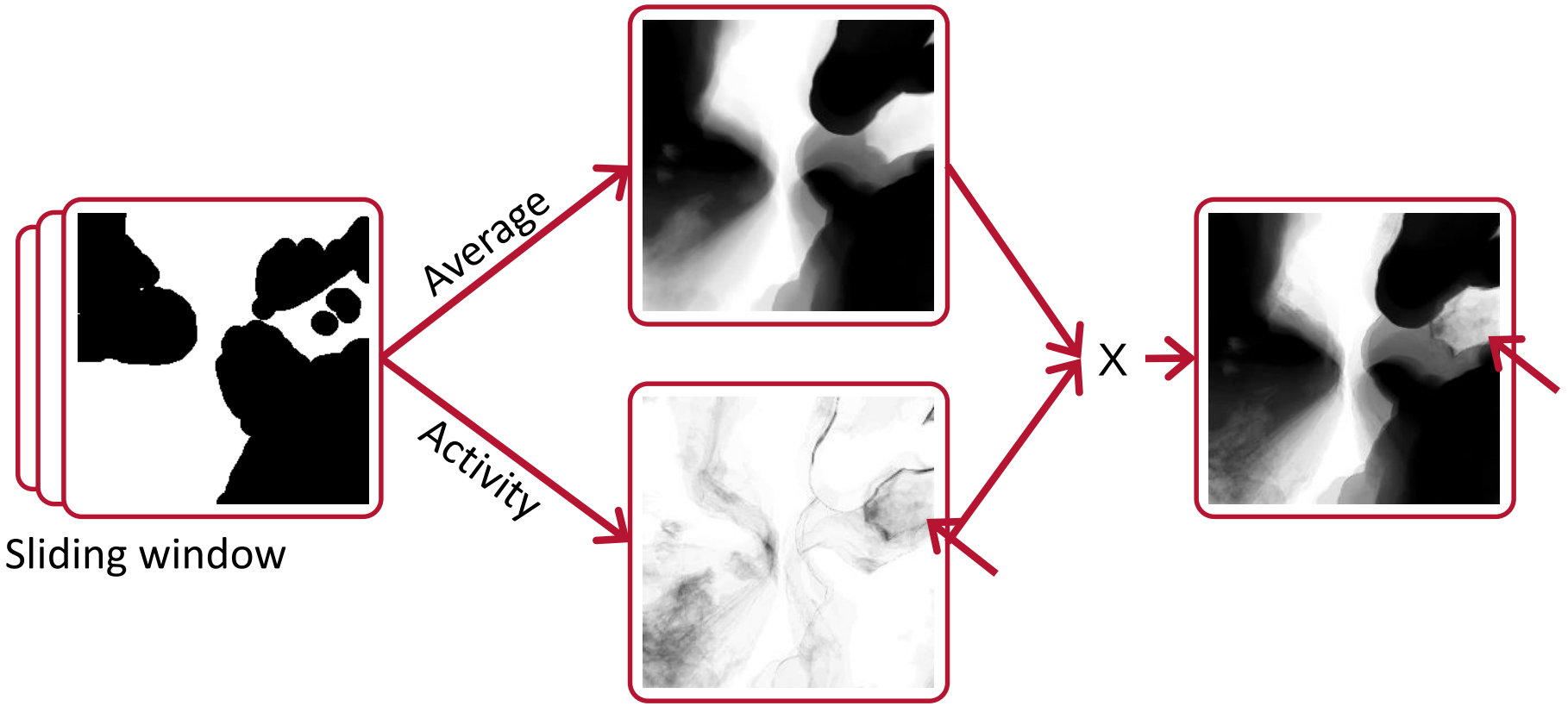


Autonomous Surgical Lamps – Pipeline



Autonomous Surgical Lamps

- Find positions with high likelihood of staying occlusion-free
- Goal: capture temporal coherence in one map



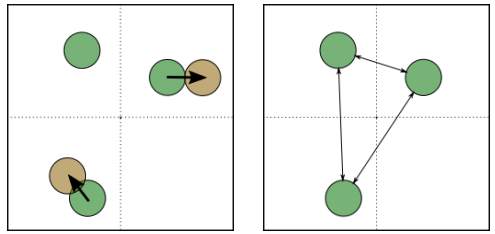
Our Objective Function for Runtime Optimization

Weights

$$w_{occl}, w_{move}, w_{temp}, w_{dist}$$

Workspace maps

Lamp positions



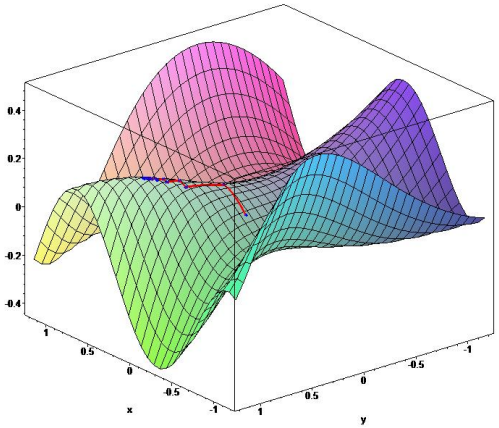
Objective function

Cost

$$C(\mathcal{L}) = w_{dist} d(L_i, L_j) + \sum_{i=1}^{|\mathcal{L}|} w_{temp} I_{temp}(L_i) + w_{occ} I_{occ}(L_i) + w_{move} d(L_i^t, L_i^{t+1})$$

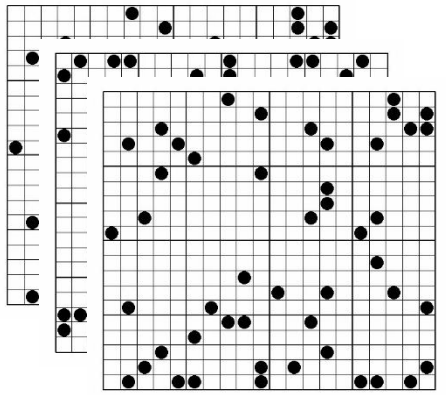
where $\mathcal{L} = \{L_1, \ldots, L_n\}$ is the set of all lamps' positions.

Our Old Optimization Method

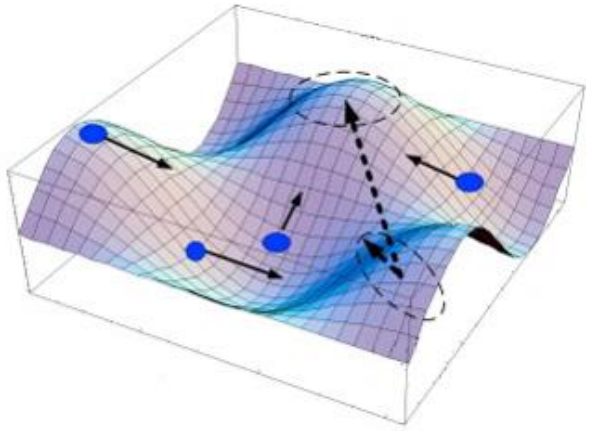


- Every frame: (if necessary) steepest descend
  - From current lamp positions
  - On fitness values
  - Towards local optimum

- If current optimum is below threshold:
  - Start a random sampling of the entire search space



Our New Runtime-Optimization



- Use Particle Swarm Optimization

- Each particle ≙ configuration of complete set of lamps
  - One particle = current configuration of the lamps
  - All other particles = randomly generated configurations

Meta-Optimization

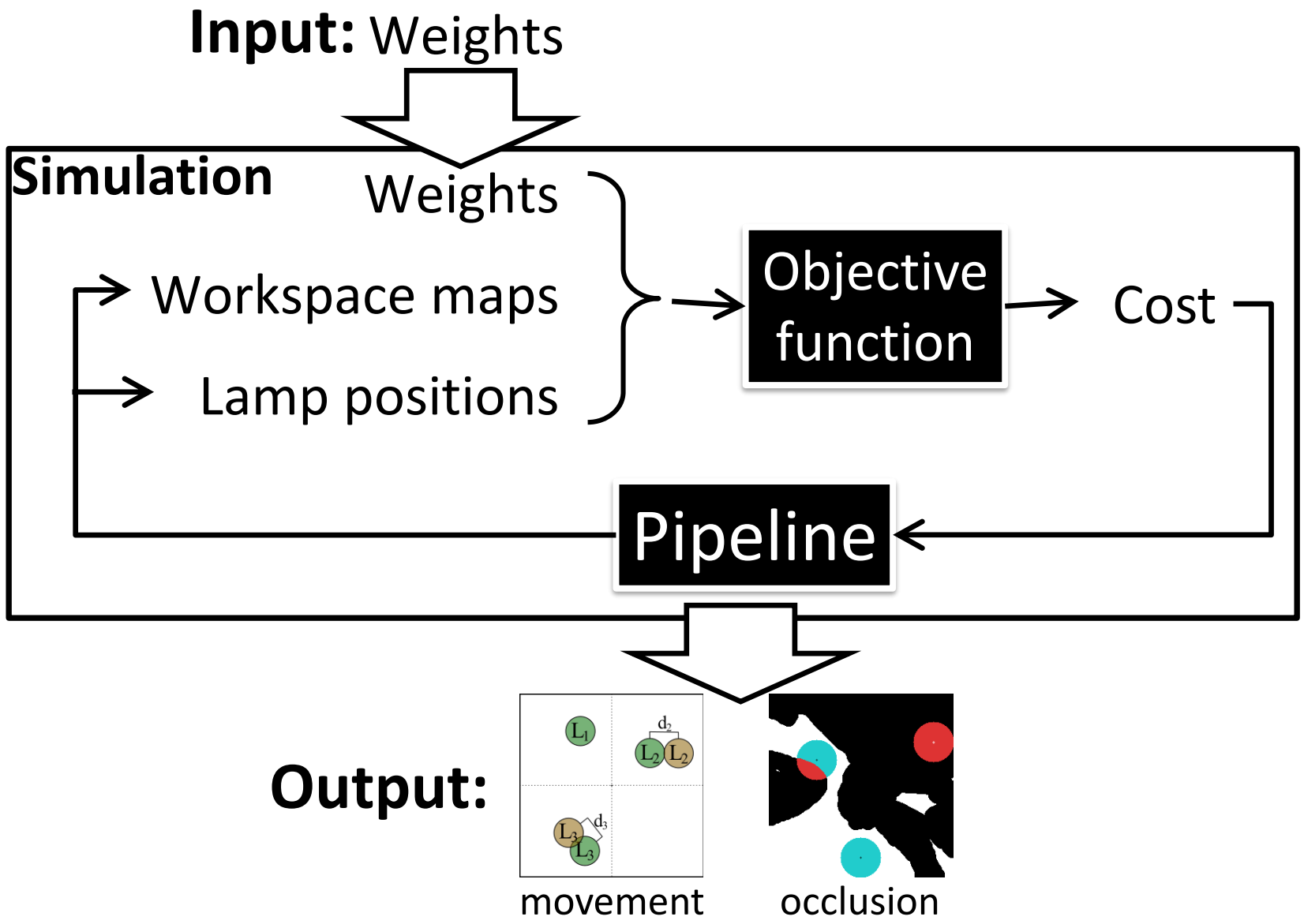
- Problem: complex relationships between weights
- Observation: movement+distribution of occluders consistent
- Idea: do machine learning on recorded intervention

- Recorded a 6-hour open, abdominal intervention
- Picked a 6-minute part to optimize the weights

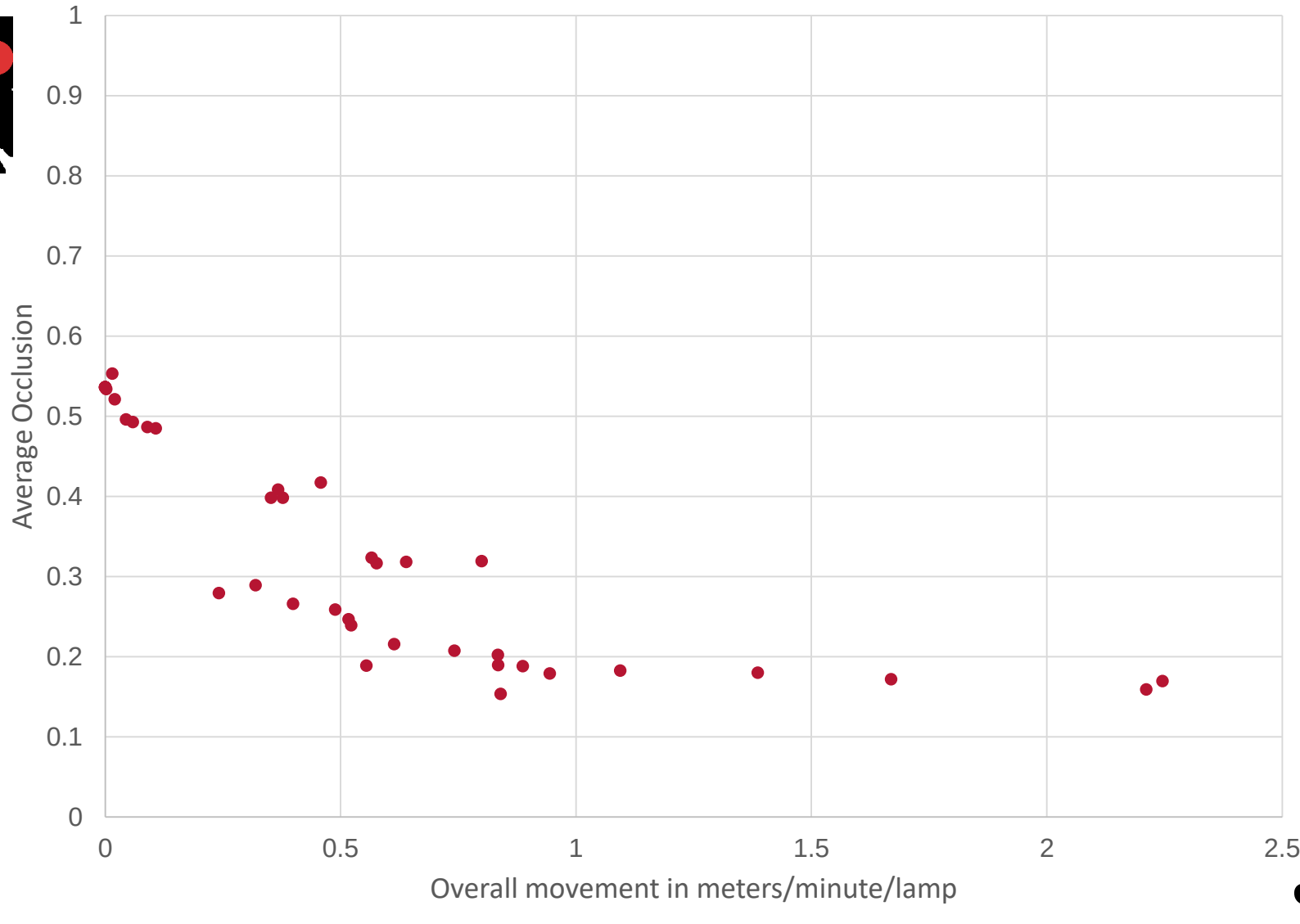
Meta-Optimization

- Uses non-dominated sorting particle swarm optimization [Li, X., 2003]
  - Good for non-trivial Pareto-fronts
- Results should be:
  - Useful for the surgeon
  - Easy to understand
  - Reflecting the original optimization goals

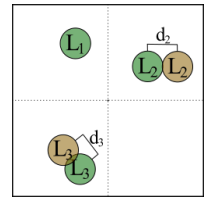
Meta-Optimization Objective Function



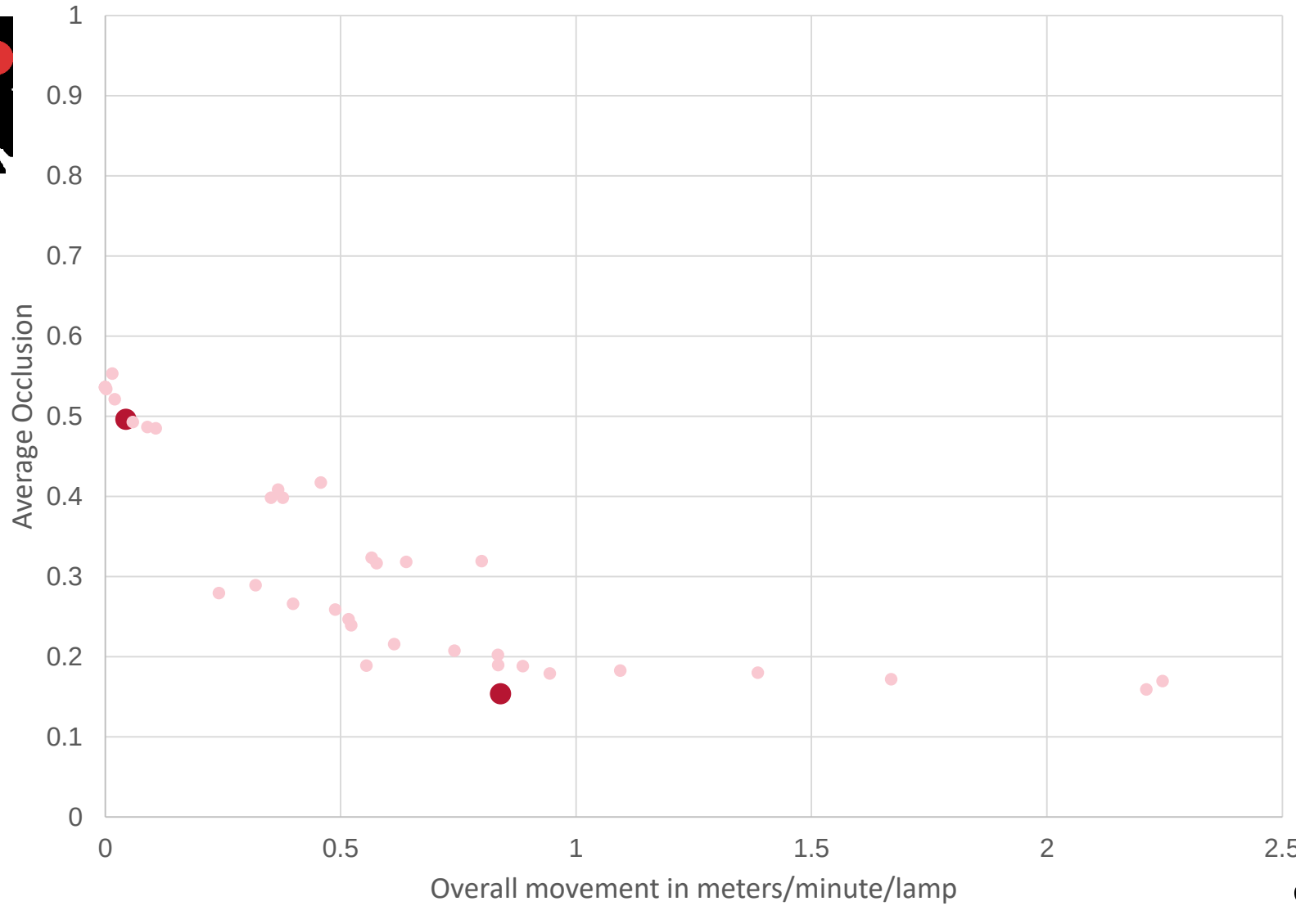
Results



$$\int_{t=0}^{n}$$



Results



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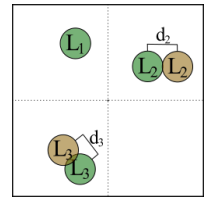
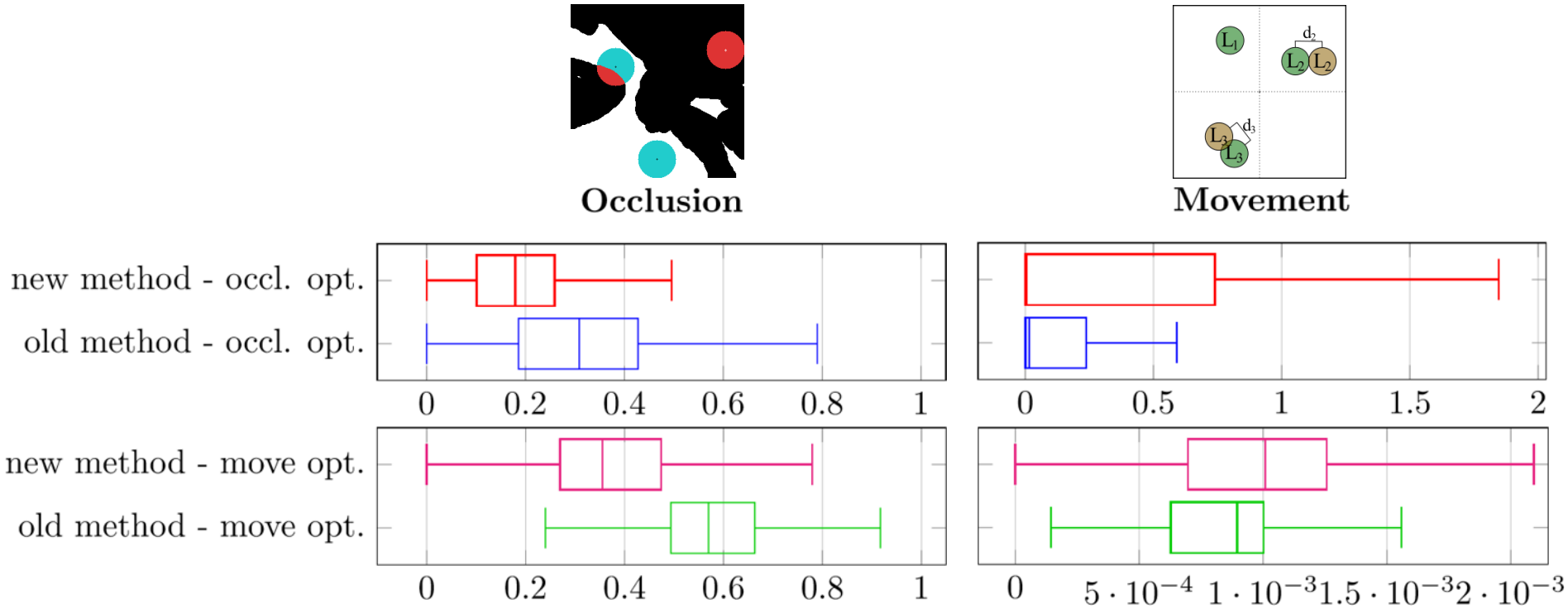


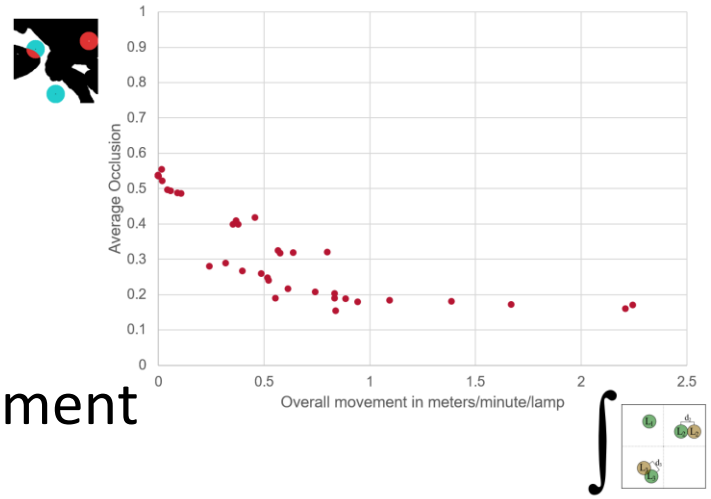
Results

- Is the solution stable for entire intervention?
- Test solutions on different part (~15 mins) of intervention



Conclusion

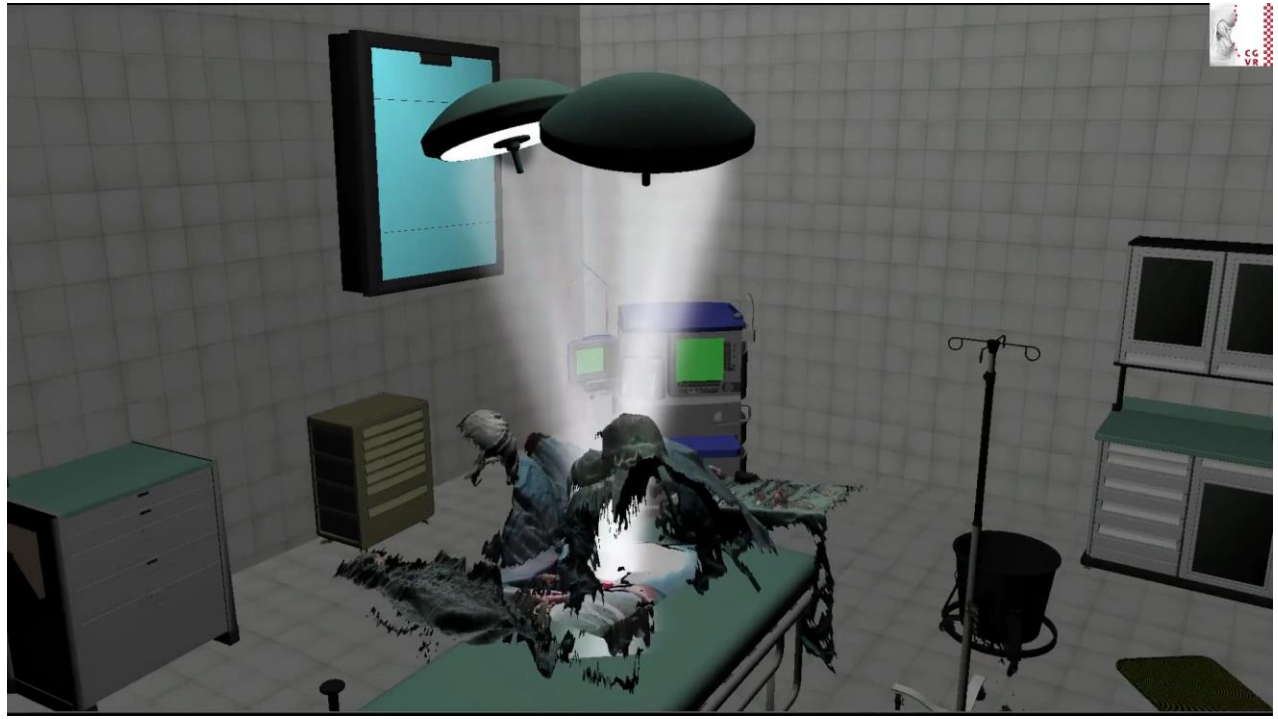
- Novel two-tiered optimization scheme
  - Scalarized optimization at runtime
  - Multi-objective meta-optimization
- Surgeons can pick lamp behavior
- Results are stable throughout intervention
- Runtime optimization with longer time without movement



Future Work

- User study: manual vs. autonomous lamp movement
- Tracking of the surgical site
- Study with quantitative measurement of lighting in site
- Try training a neural network
- Better simulation of lighting

Thank you for your attention!



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Data and video can be found at

cgvr.cs.uni-bremen.de/research/asula