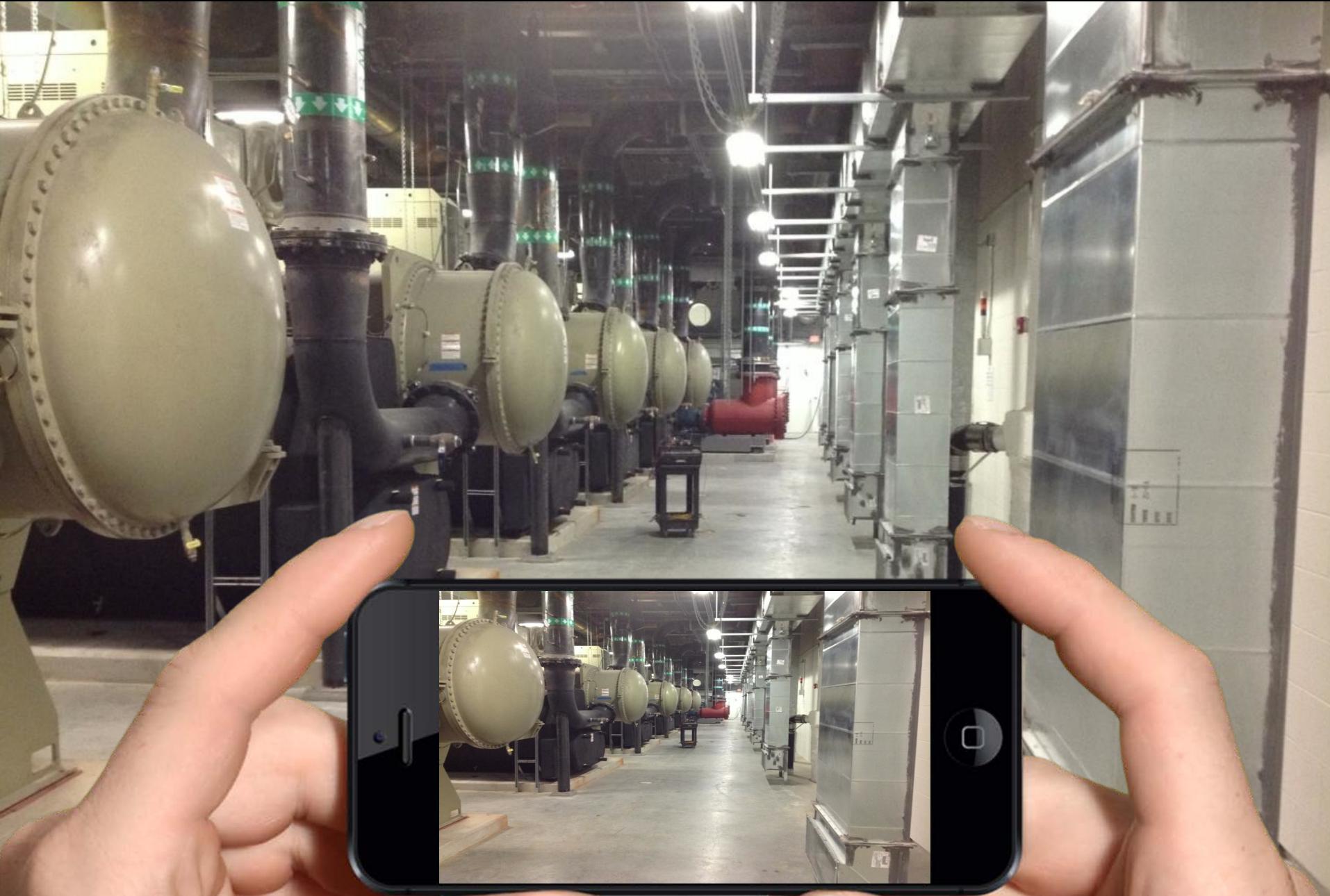


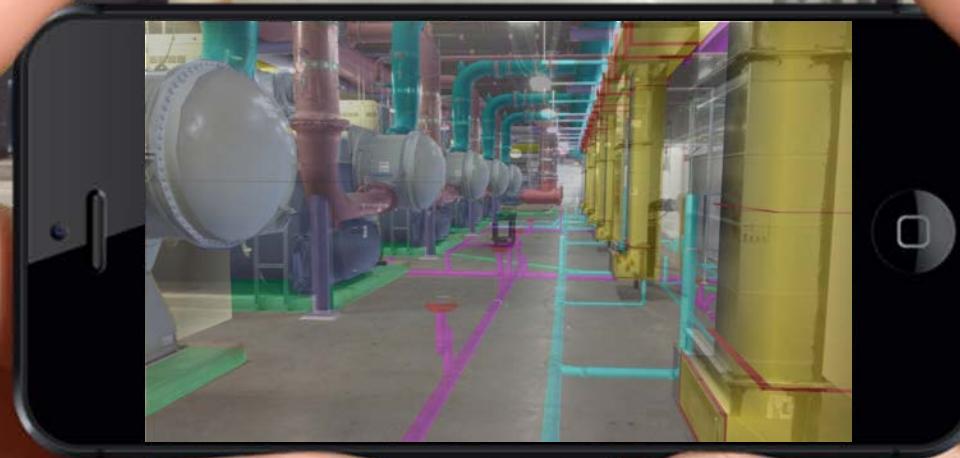
ConstructAide: Analyzing and Visualizing Construction Sites through Photographs and Building Models

Kevin Karsch Mani Golparvar-Fard David Forsyth
University of Illinois

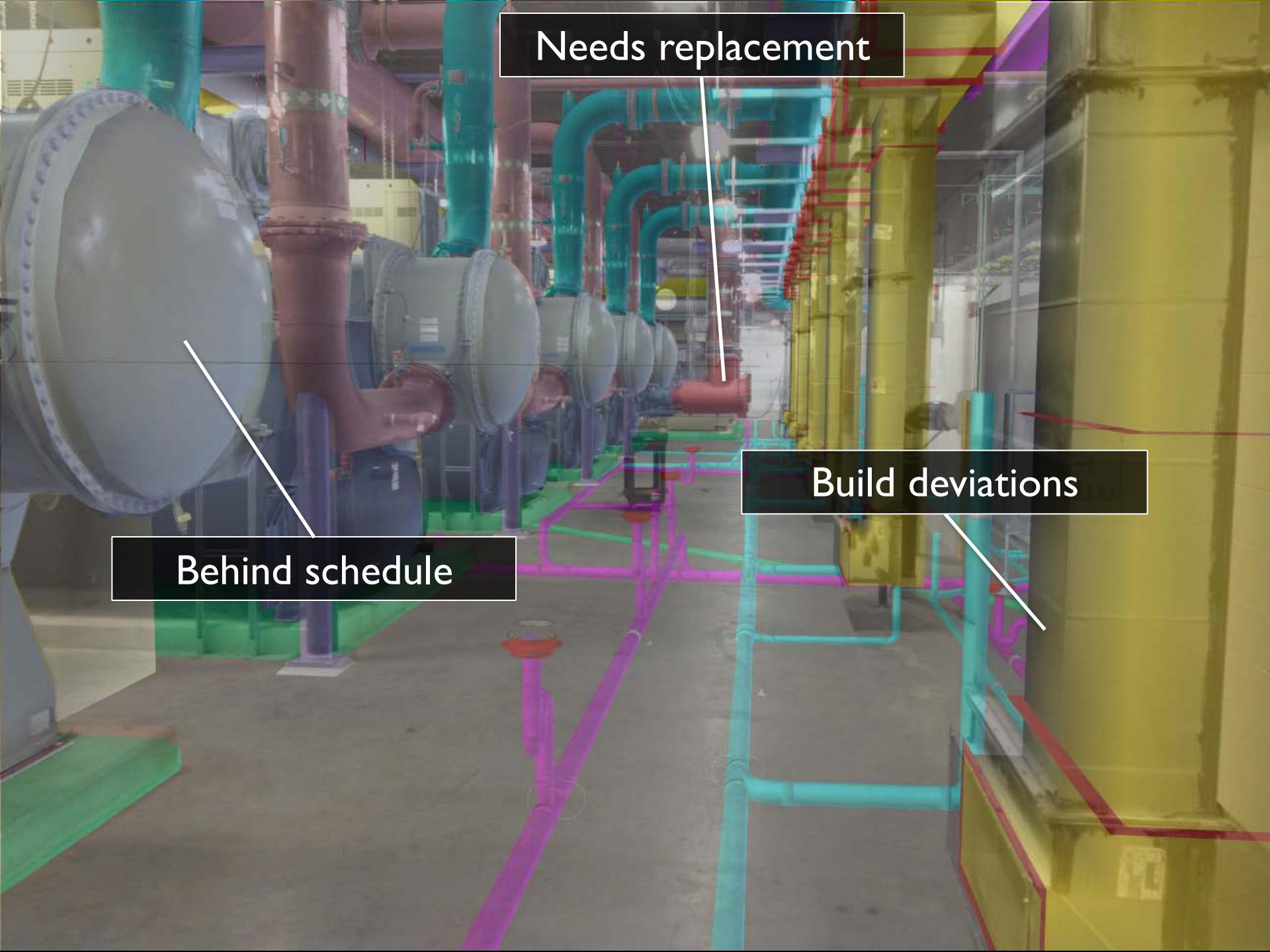










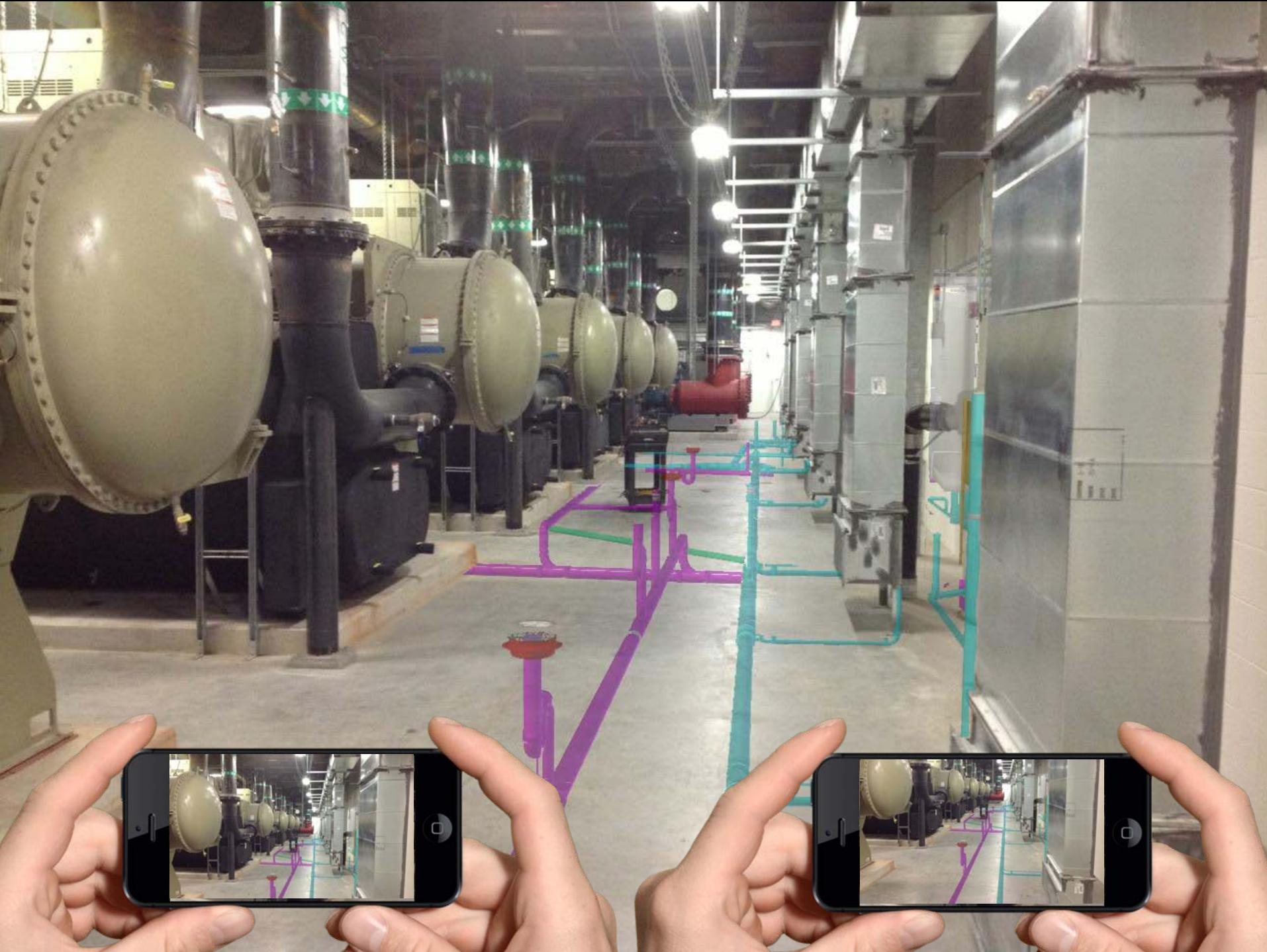


Needs replacement

Behind schedule

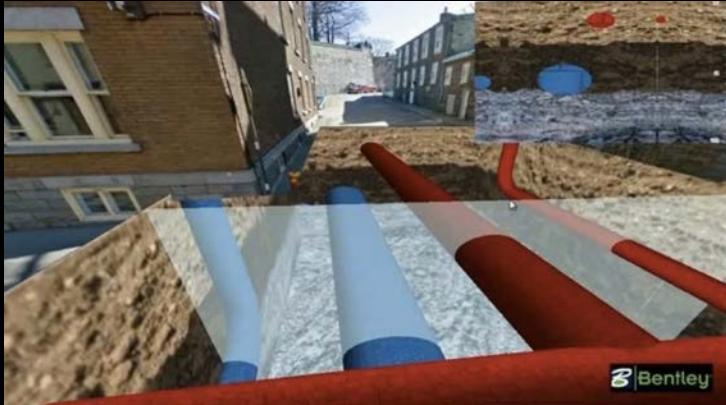
Build deviations





Existing Techniques

Existing Techniques



Manual registration + hardware tracking
[Cote et al. 2013, 2011; Hakkarainen et al. 2009; Irizarry et al. 2012; Woodward et al. 2010; Lee and Akin 2011; Shin and Dunston 2010; Yabuki et al. 2010]



Occlusion visualization
[Zollmann et al. 2010, 2012]



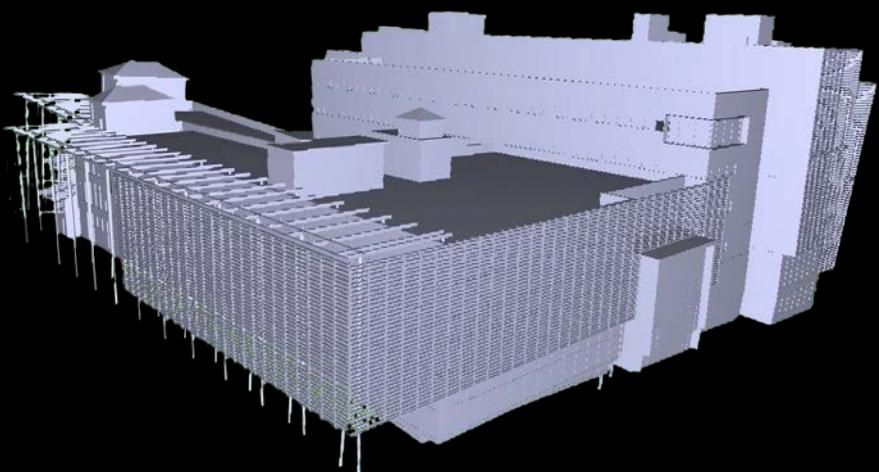
D4AR [Golparvar-Fard et al. 2011]

System Overview

System Overview

Inputs:

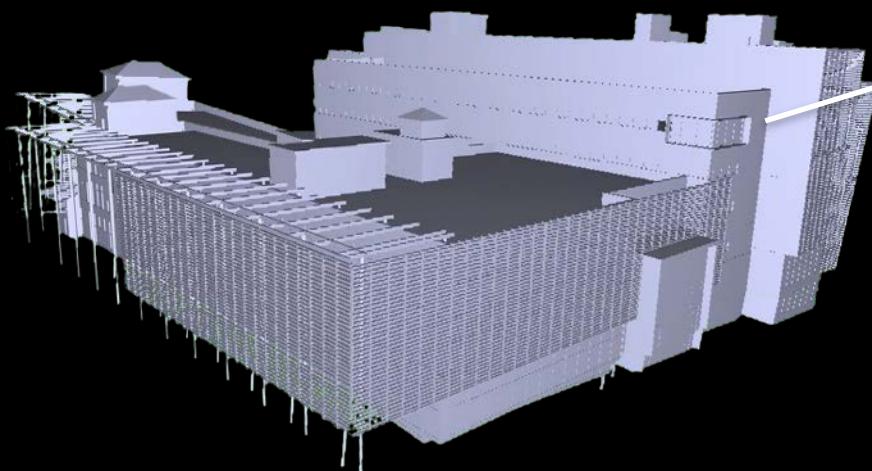
- 4D Building Information Model (BIM)



System Overview

Inputs:

- 4D Building Information Model (BIM)



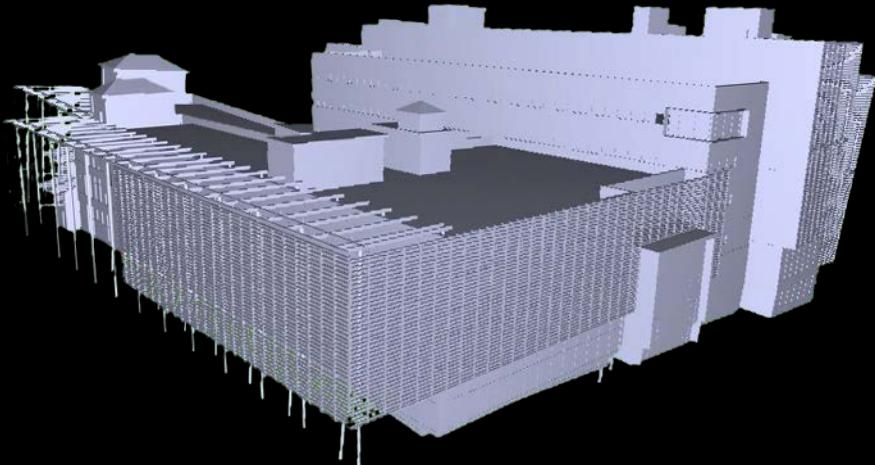
BIM data:

- Semantic 3D mesh
- Scheduling info
- Materials
- GPS data
- ...

System Overview

Inputs:

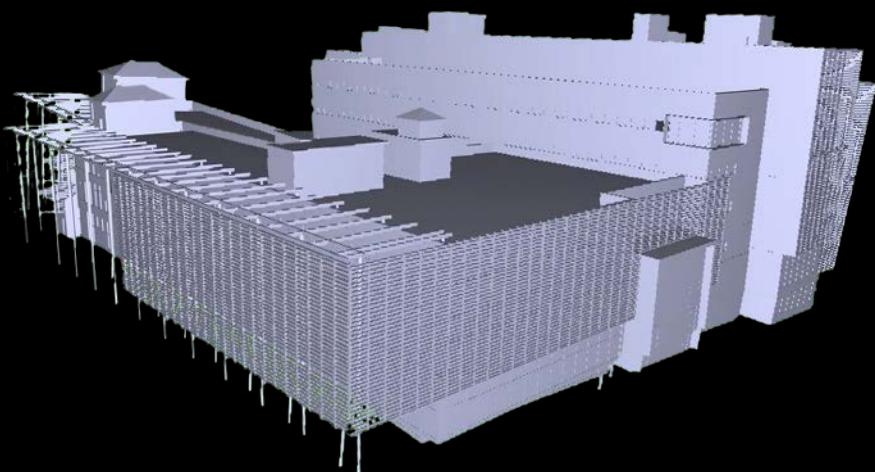
- 4D Building Information Model (BIM)
- One or more site photographs



System Overview

Inputs:

- 4D Building Information Model (BIM)
- One or more site photographs



System Overview



Model registration via Model-assisted SfM

System Overview



Model registration via Model-assisted SfM

System Overview

ConstructAide provides tools for:

- 4D navigation
- Identifying occlusions
- Visualization
- Progress monitoring



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ConstructAide provides tools for:

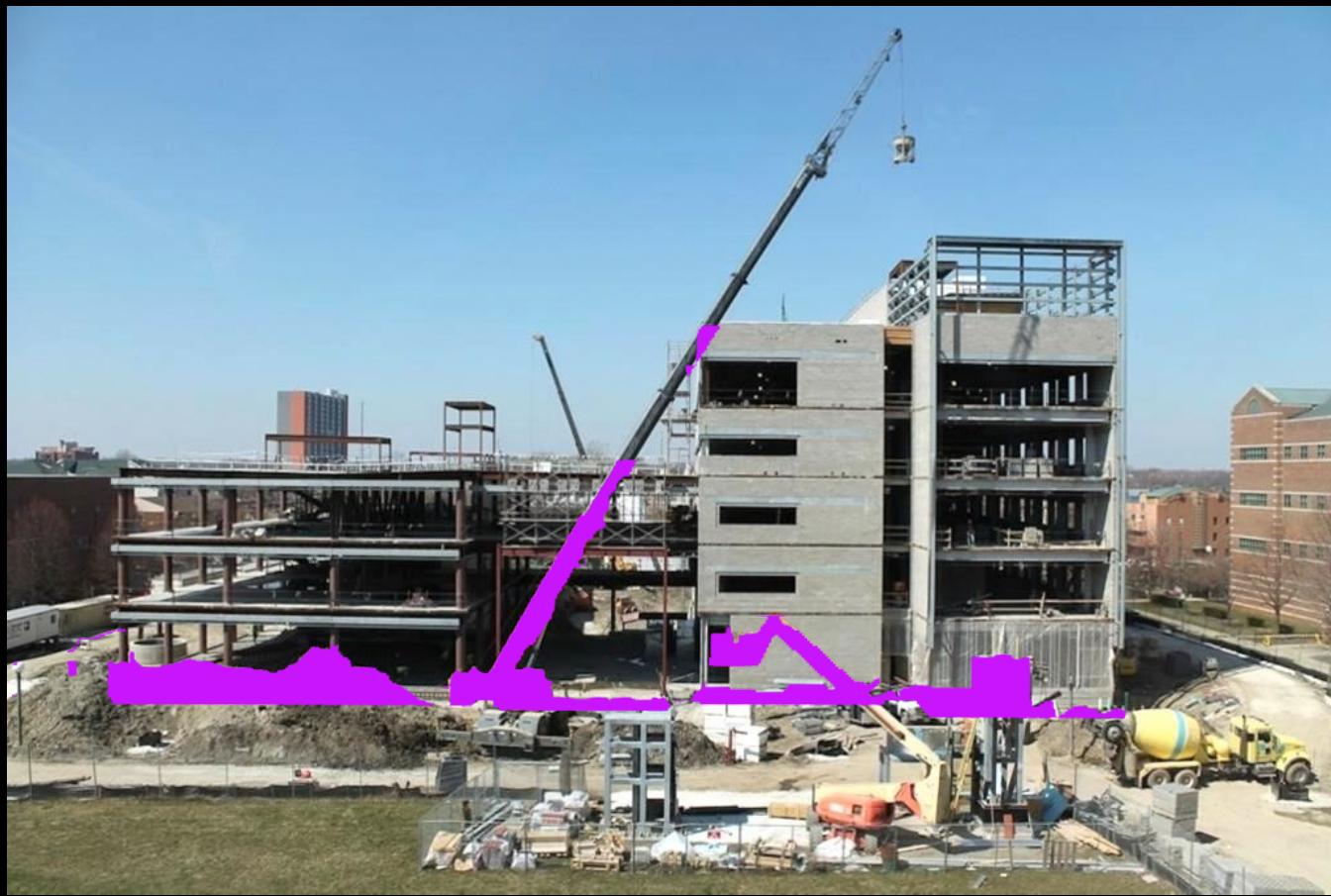
- 4D navigation
- Identifying occlusions
- Visualization
- Progress monitoring



System Overview

ConstructAide provides tools for:

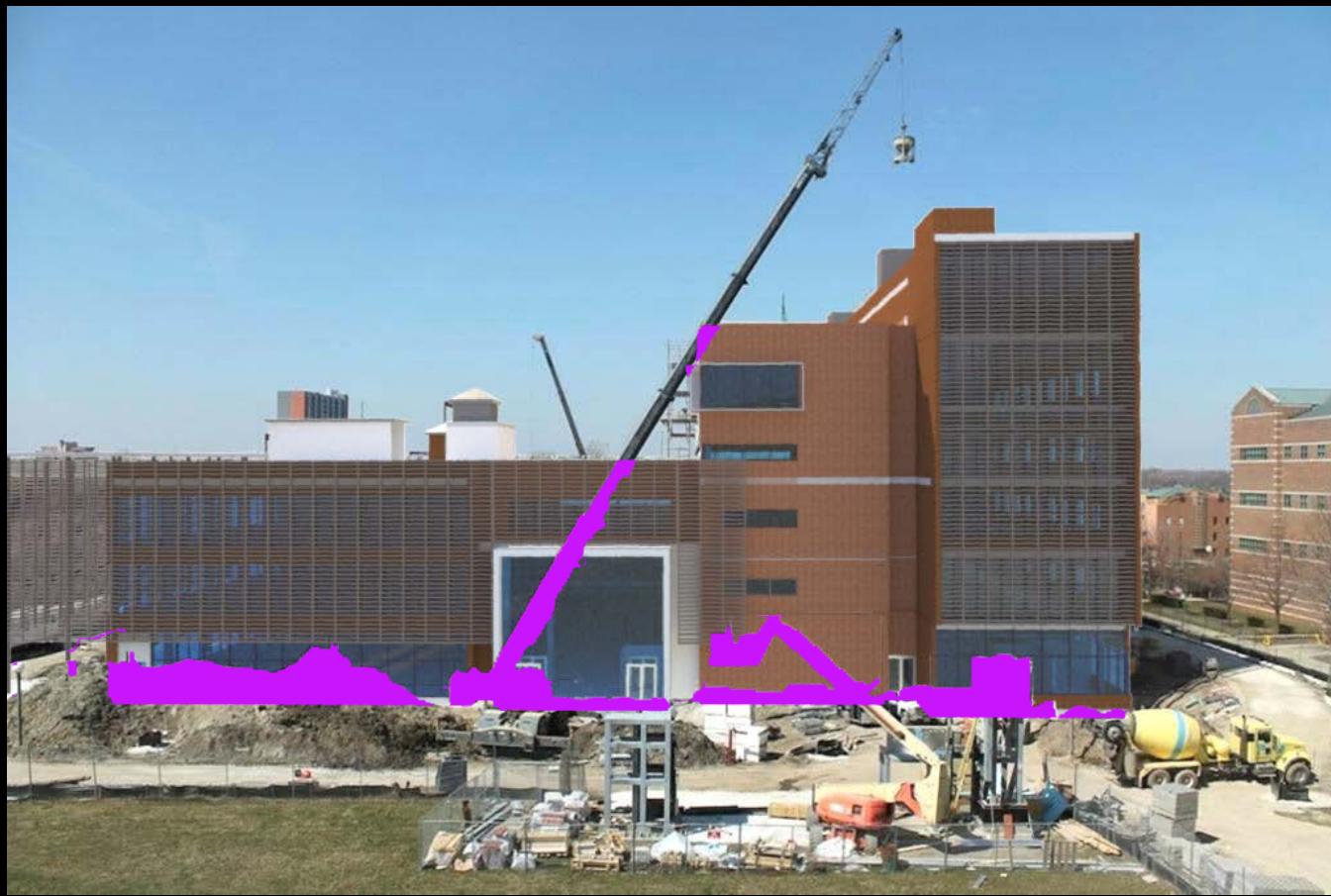
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System Overview

ConstructAide provides tools for:

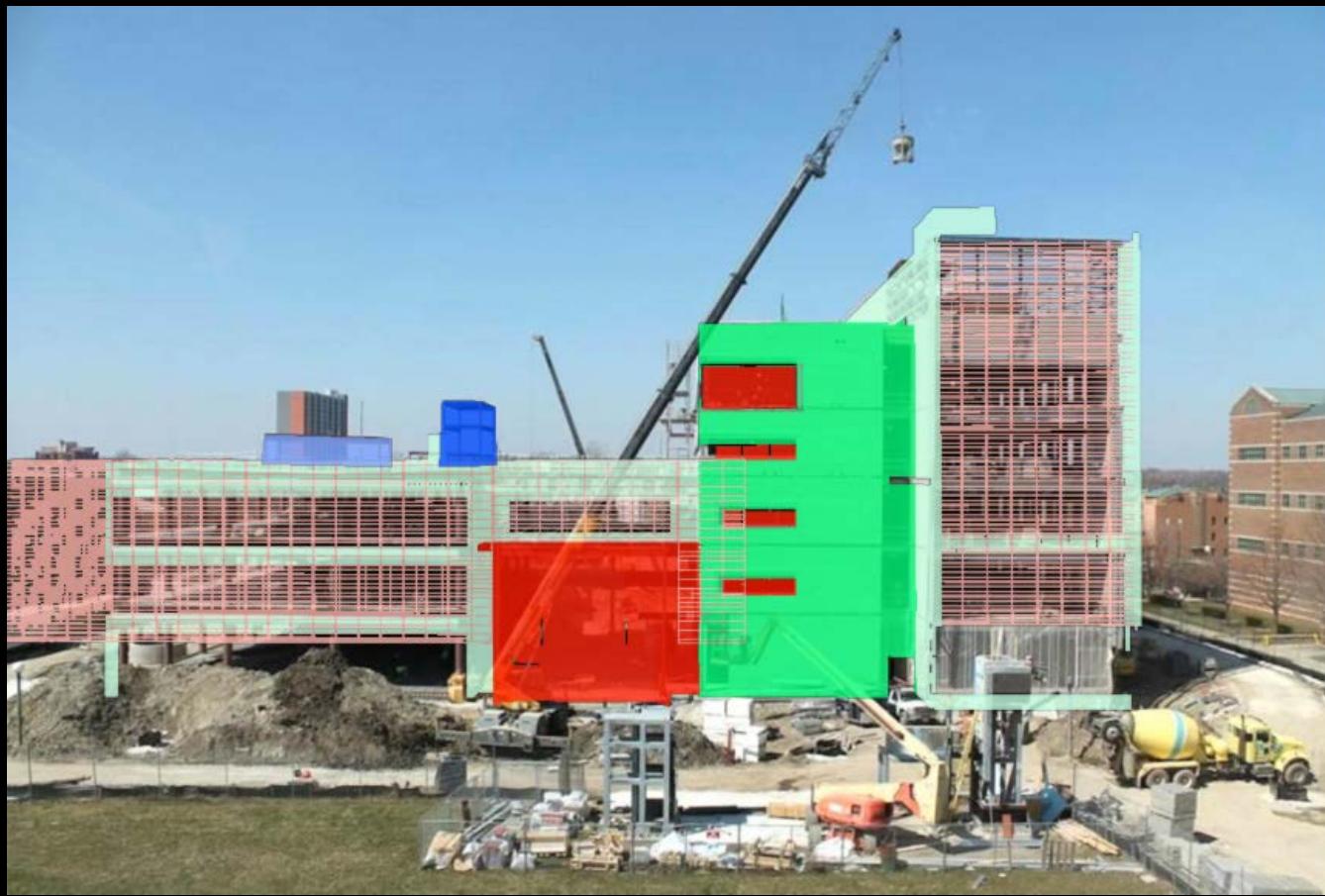
- 4D navigation
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System Overview

ConstructAide provides tools for:

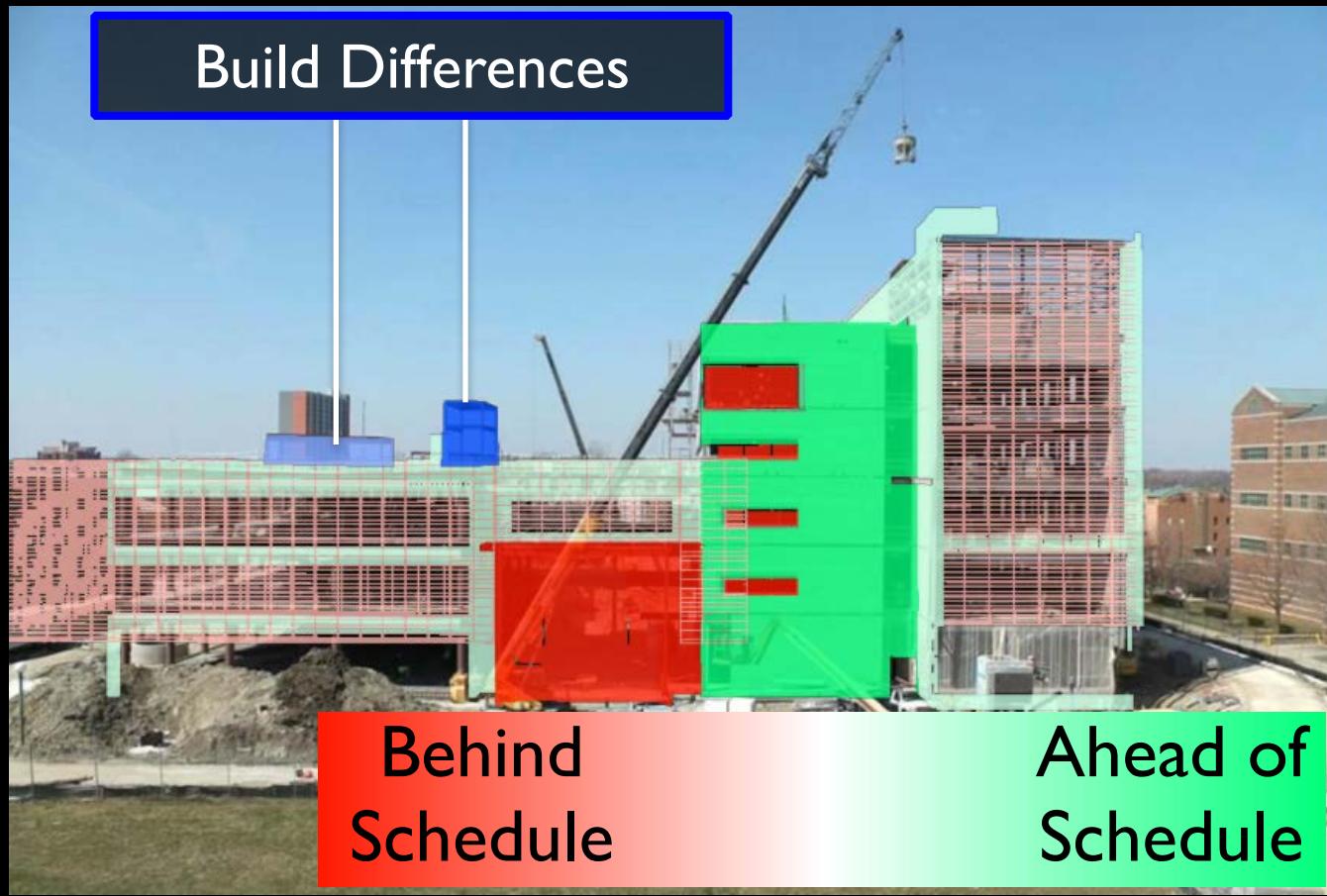
- 4D navigation
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System Overview

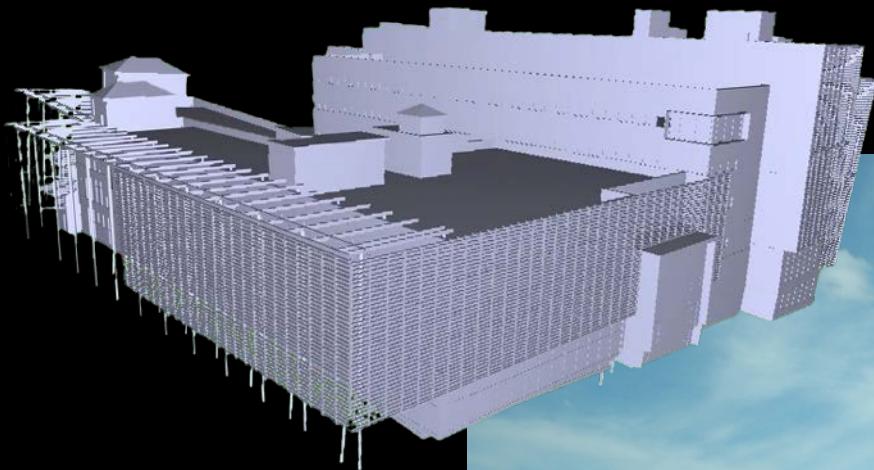
ConstructAide provides tools for:

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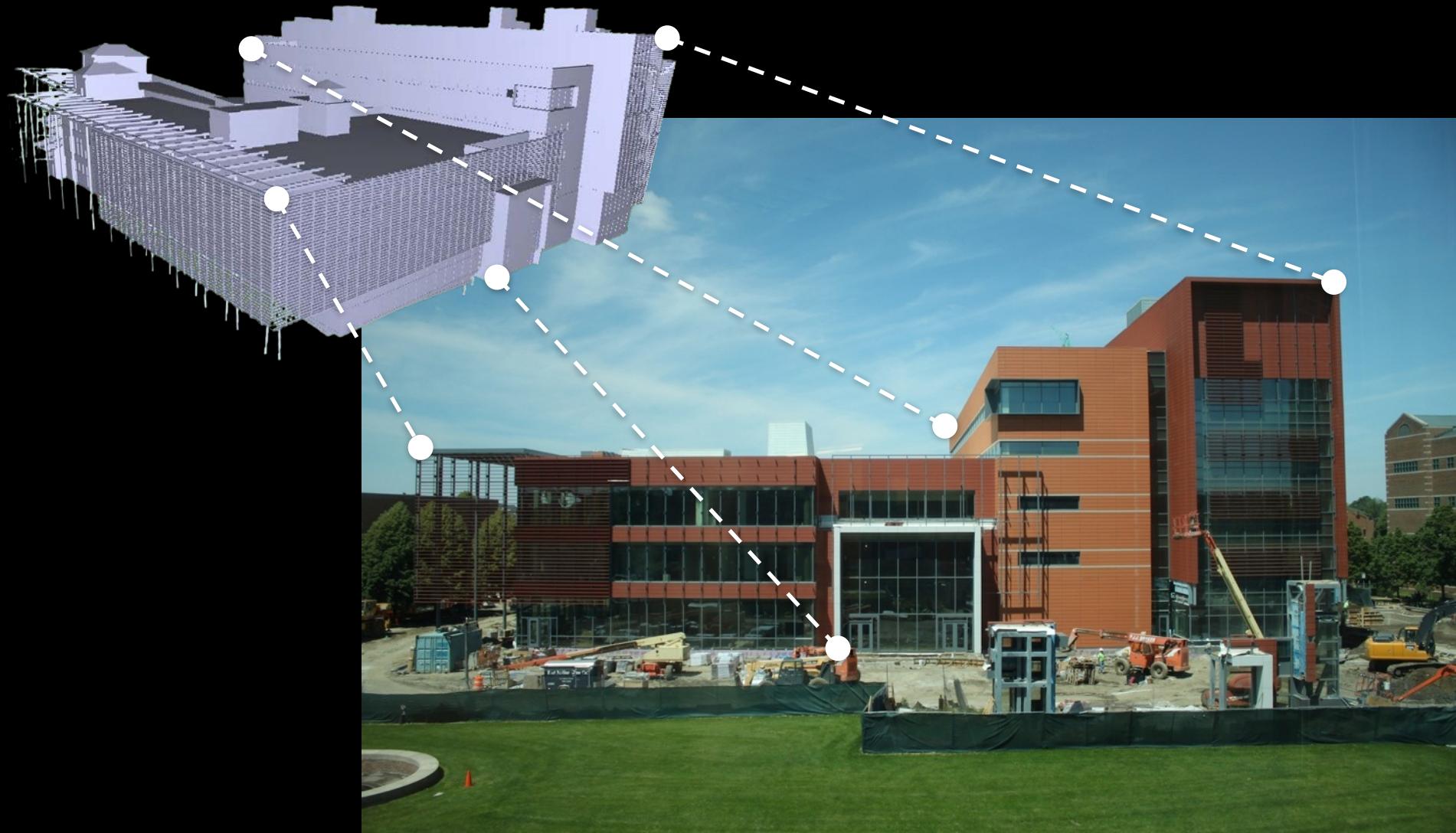


Model-assisted Structure-from-Motion

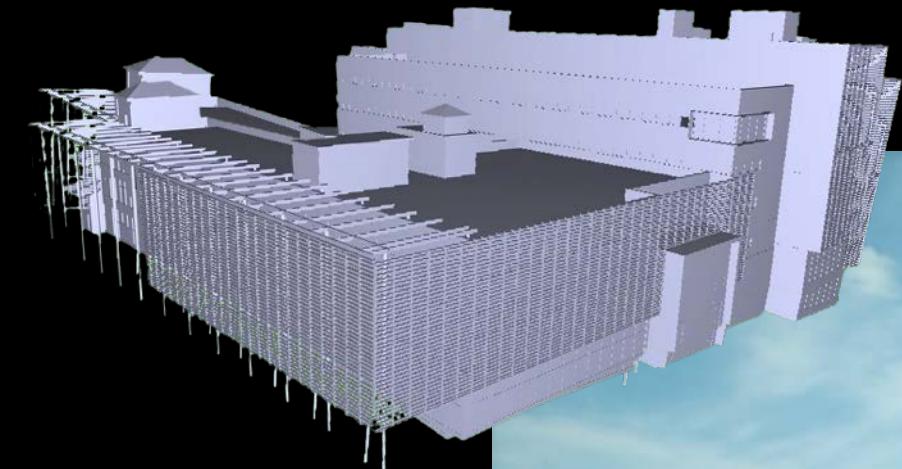
Model Registration (First Image)



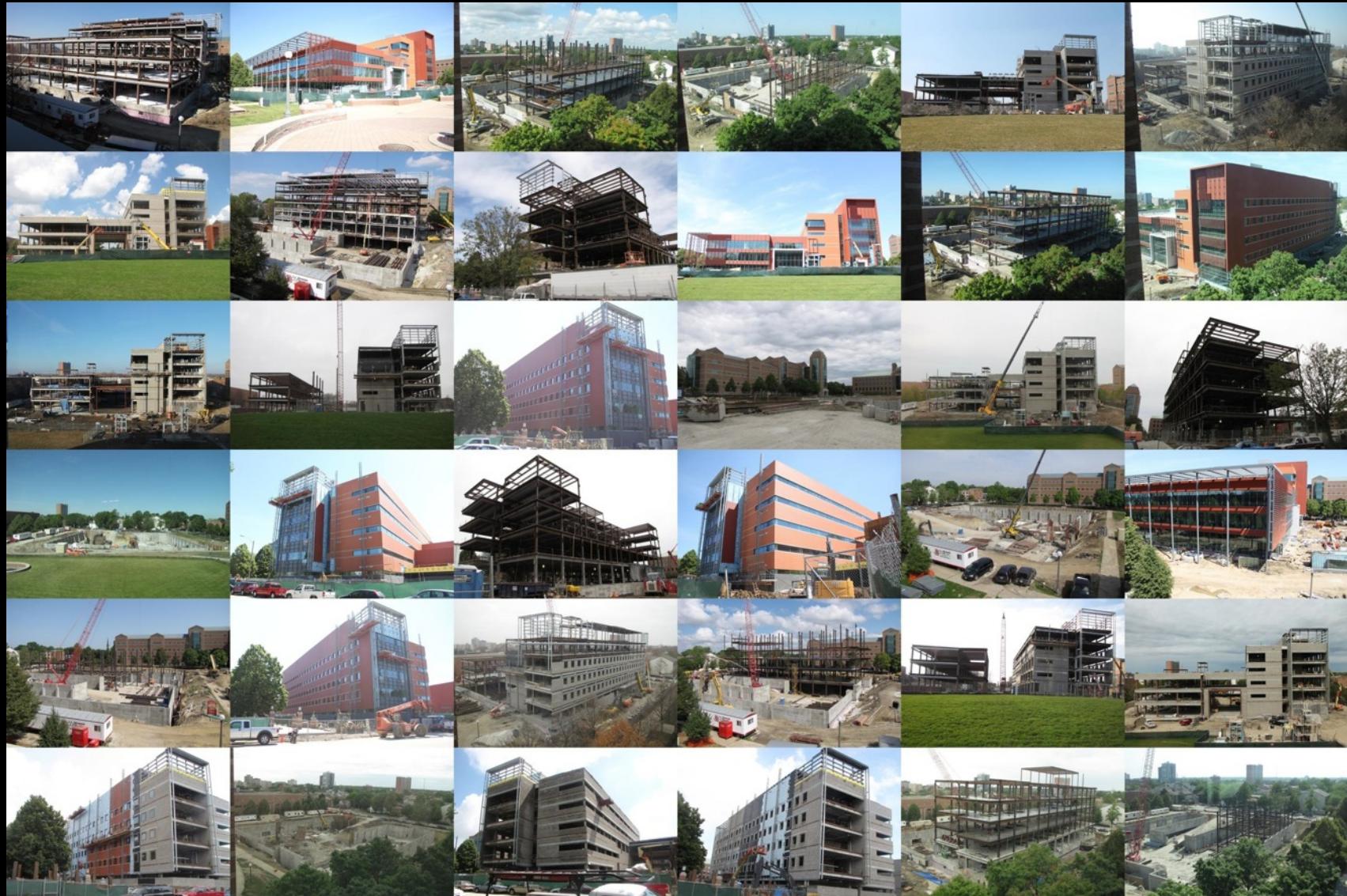
Model Registration (First Image)



Model Registration (First Image)



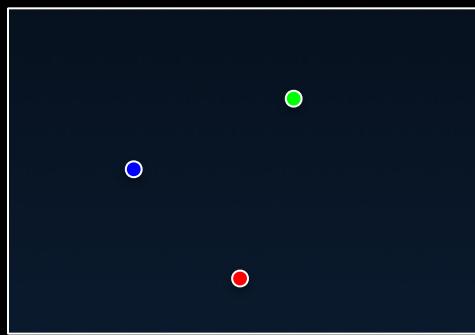
Model Registration (Subsequent Images)



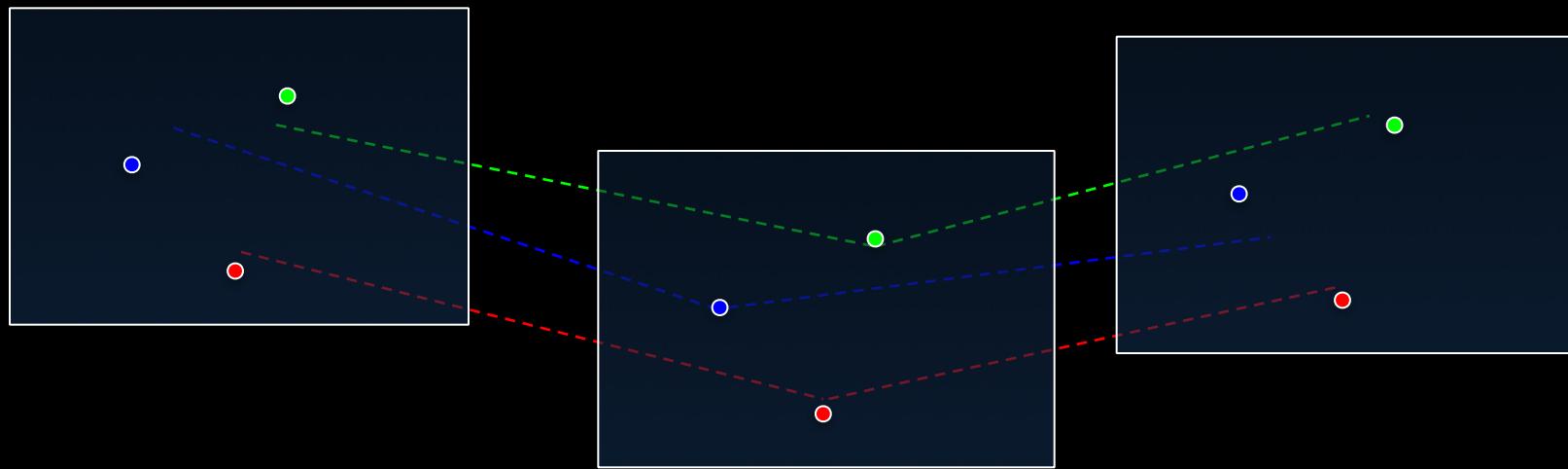
Structure-from-Motion Refresher



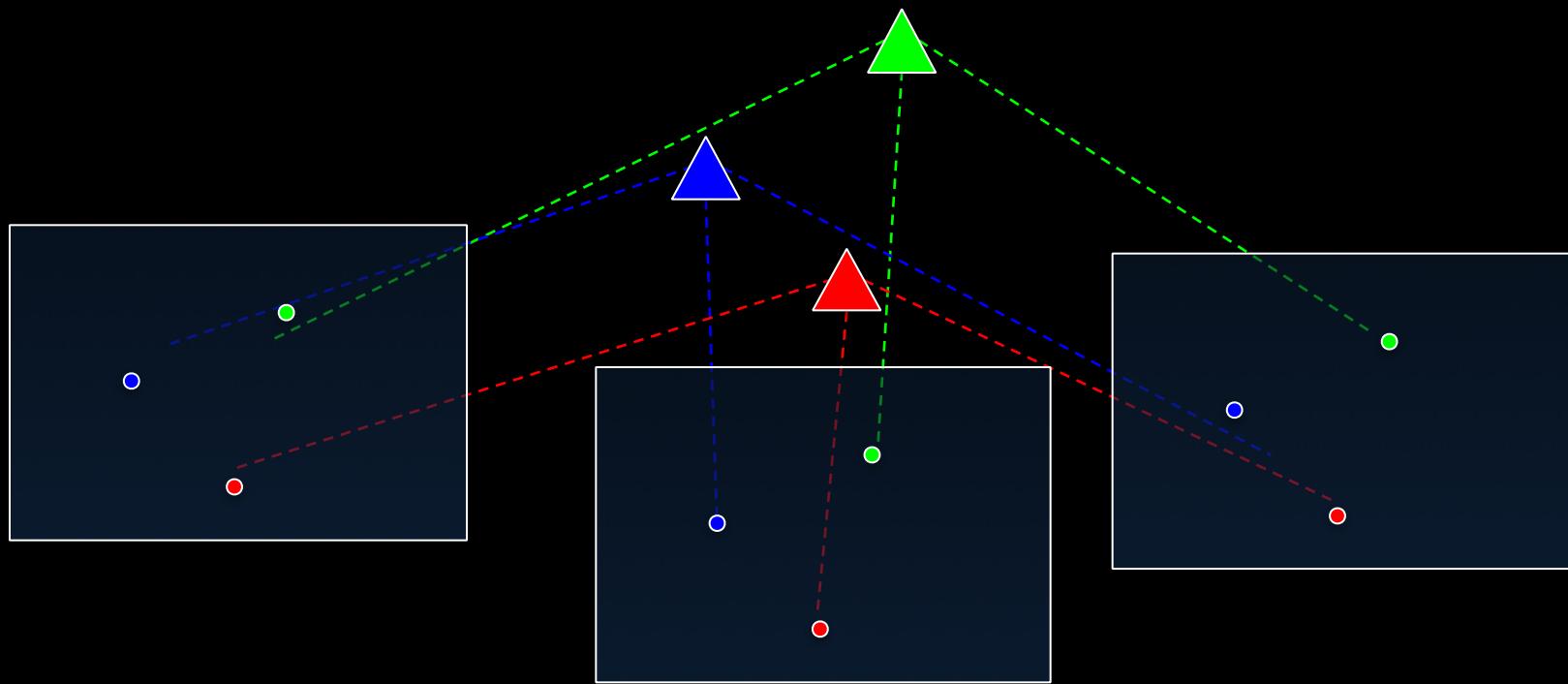
Structure-from-Motion Refresher



Structure-from-Motion Refresher

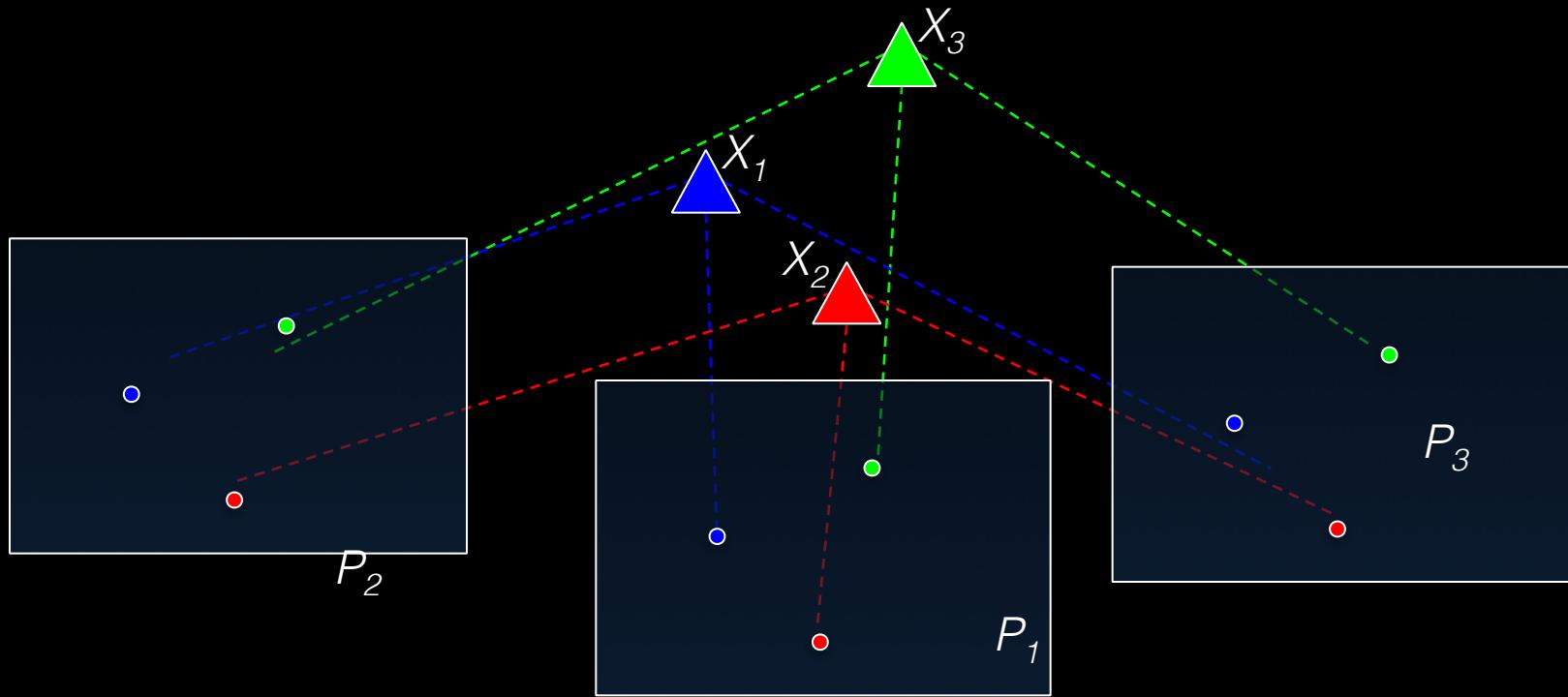


Structure-from-Motion Refresher



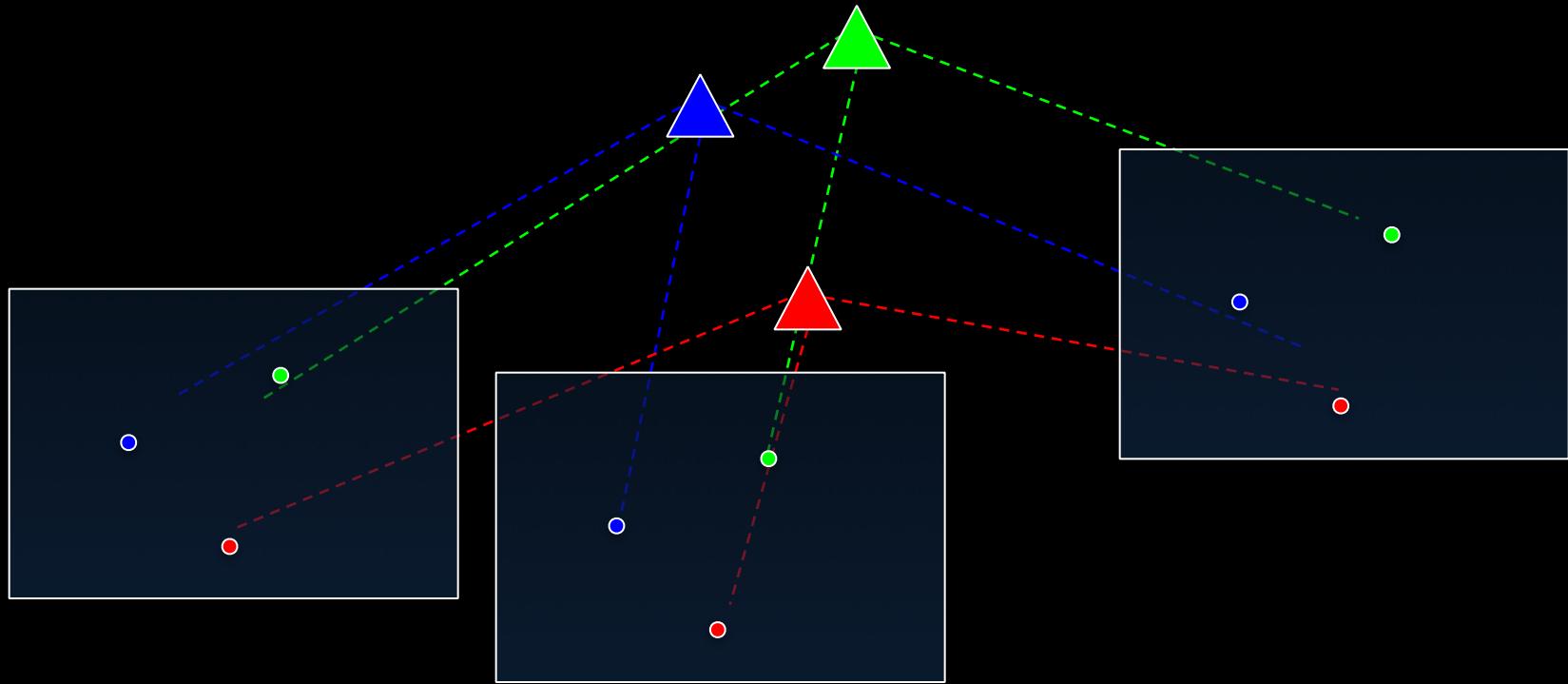
$$\underset{X, P_1, \dots, P_k}{\operatorname{argmin}} \sum_{i=1}^{\# \text{cameras}} \sum_{j=1}^{\# \text{tracks}} \delta_{i,j} \|x_j - P_i(X_j)\|$$

Structure-from-Motion Refresher



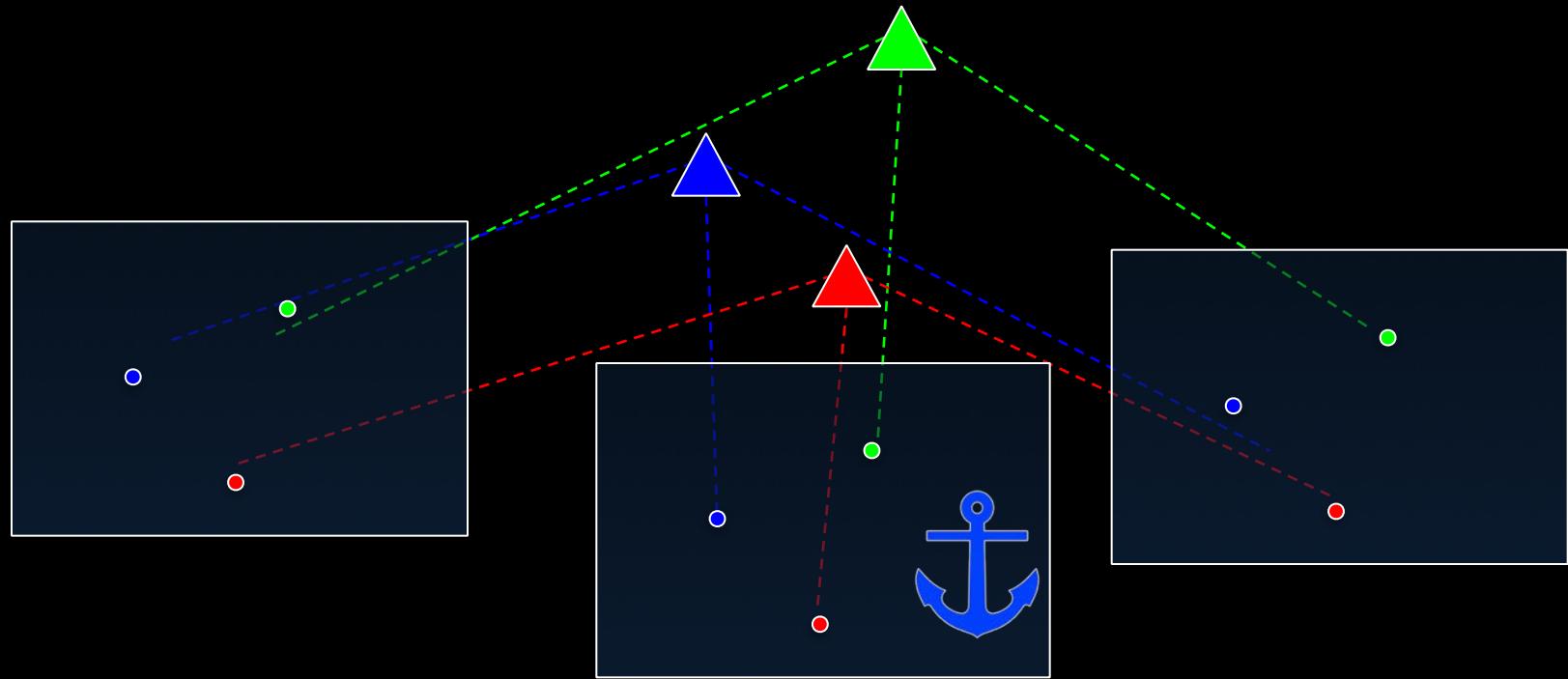
$$\underset{X, P_1, \dots, P_k}{\operatorname{argmin}} \sum_{i=1}^{\# \text{cameras}} \sum_{j=1}^{\# \text{tracks}} \delta_{i,j} \|x_j - P_i(X_j)\|$$

Structure-from-Motion Refresher



$$\underset{X, P_1, \dots, P_k}{\operatorname{argmin}} \quad \sum_{i=1}^{\# \text{cameras}} \quad \sum_{j=1}^{\# \text{tracks}} \delta_{i,j} \|x_j - P_i(X_j)\|$$

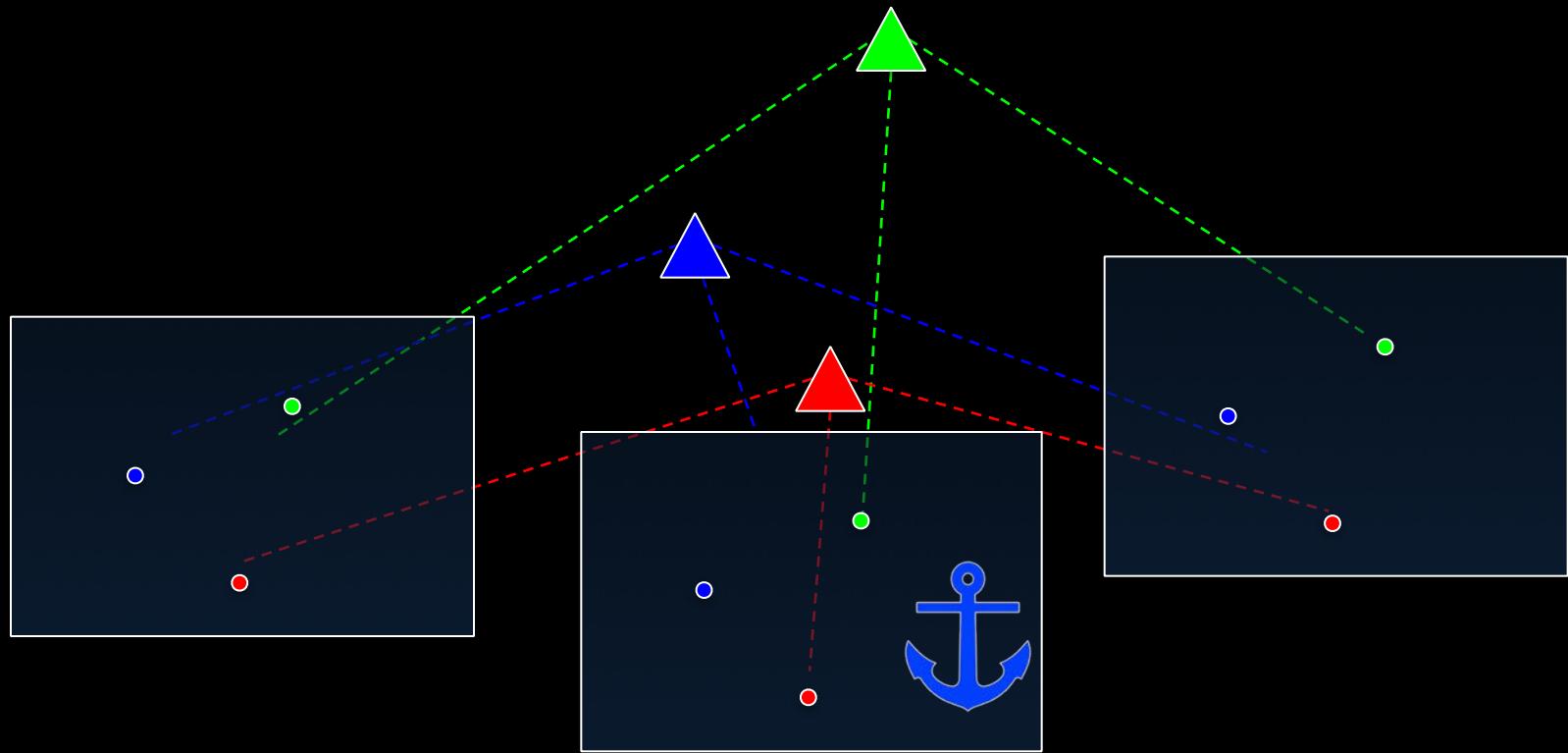
Constrained Structure-from-Motion



#cameras #tracks

$$\operatorname{argmin}_{t, P_2, \dots, P_k} \sum_{i=2}^{\text{#cameras}} \sum_{j=1}^{\text{#tracks}} \delta_{i,j} \|x_j - P_i(X_j(t_j))\|$$

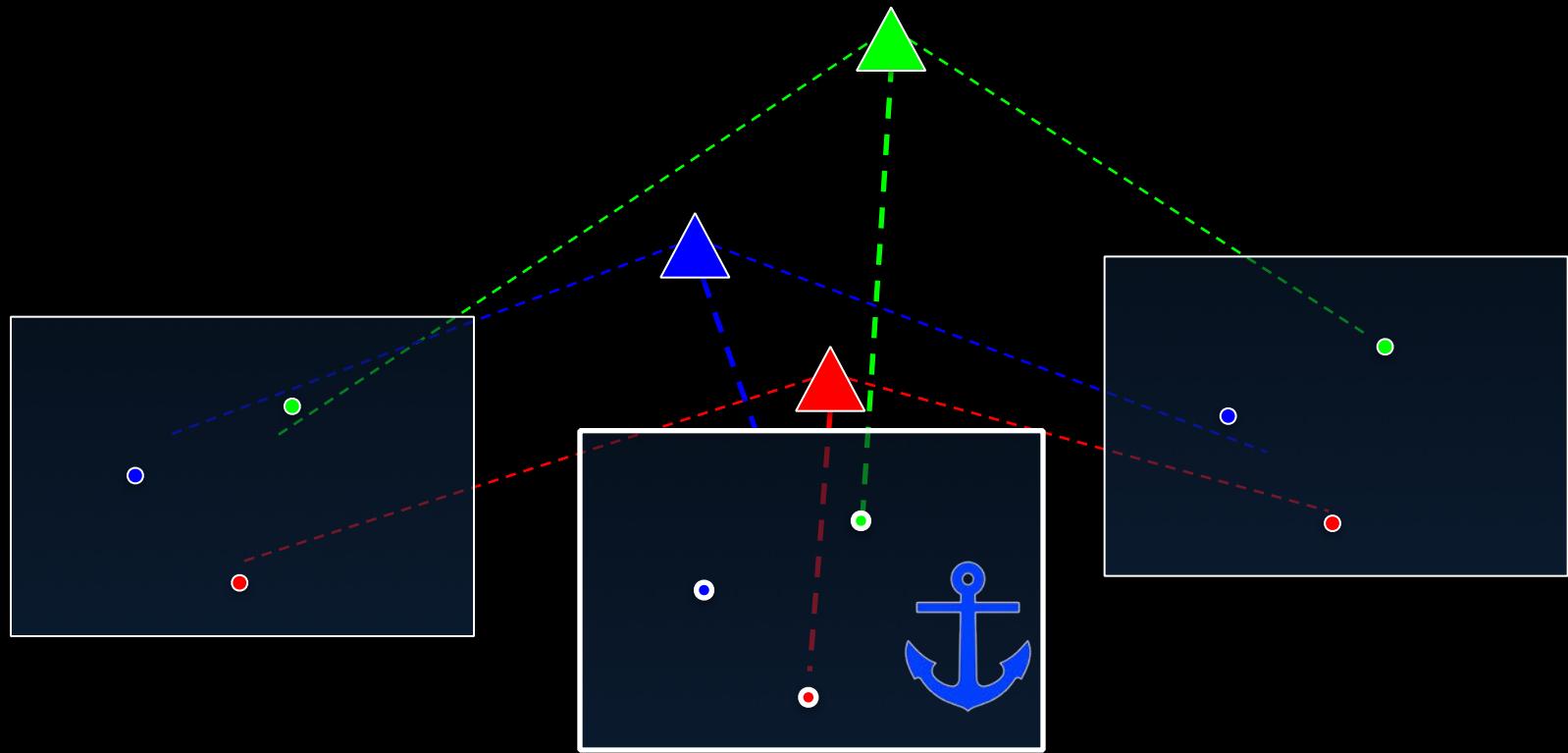
Constrained Structure-from-Motion



#cameras #tracks

$$\operatorname{argmin}_{t, P_2, \dots, P_k} \sum_{i=2}^{\text{#cameras}} \sum_{j=1}^{\text{#tracks}} \delta_{i,j} \|x_j - P_i(X_j(t_j))\|$$

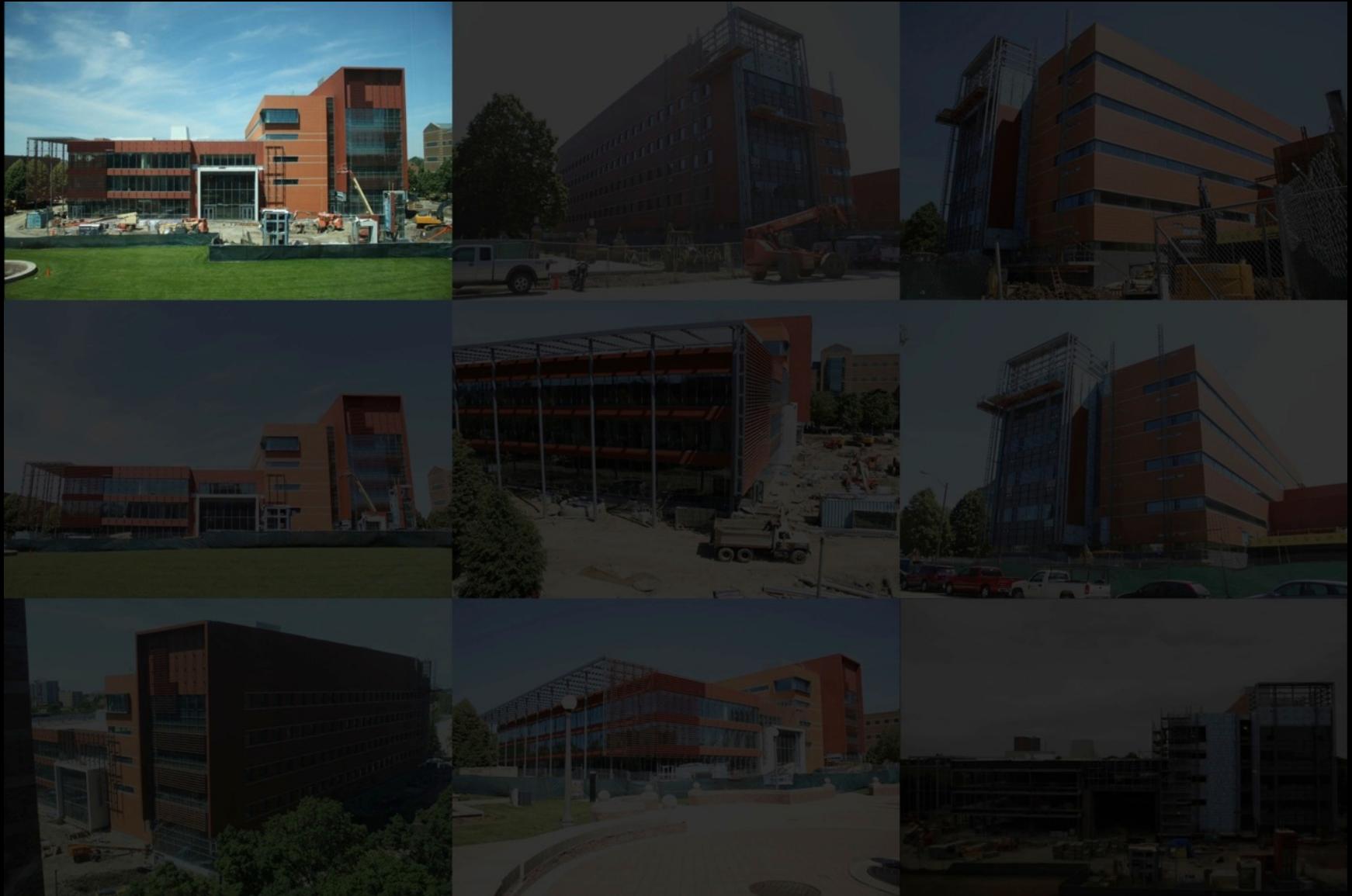
Constrained Structure-from-Motion



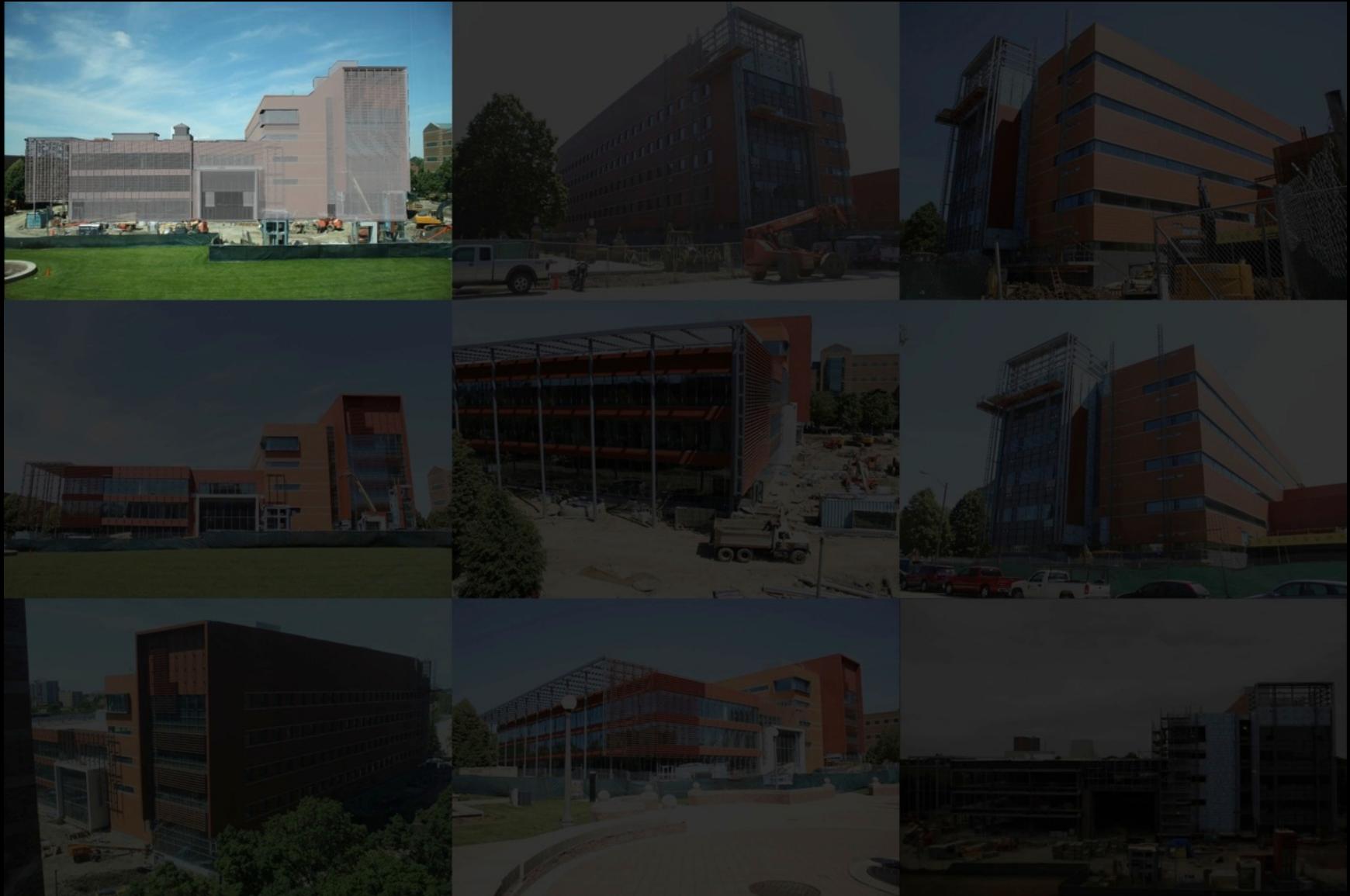
#cameras #tracks

$$\underset{\underline{t}, \underline{P_2}, \dots, \underline{P_k}}{\operatorname{argmin}} \sum_{i=2}^{\# \text{cameras}} \sum_{j=1}^{\# \text{tracks}} \delta_{i,j} \left\| \underline{x_j} - \underline{P_i(X_j(t_j))} \right\|$$

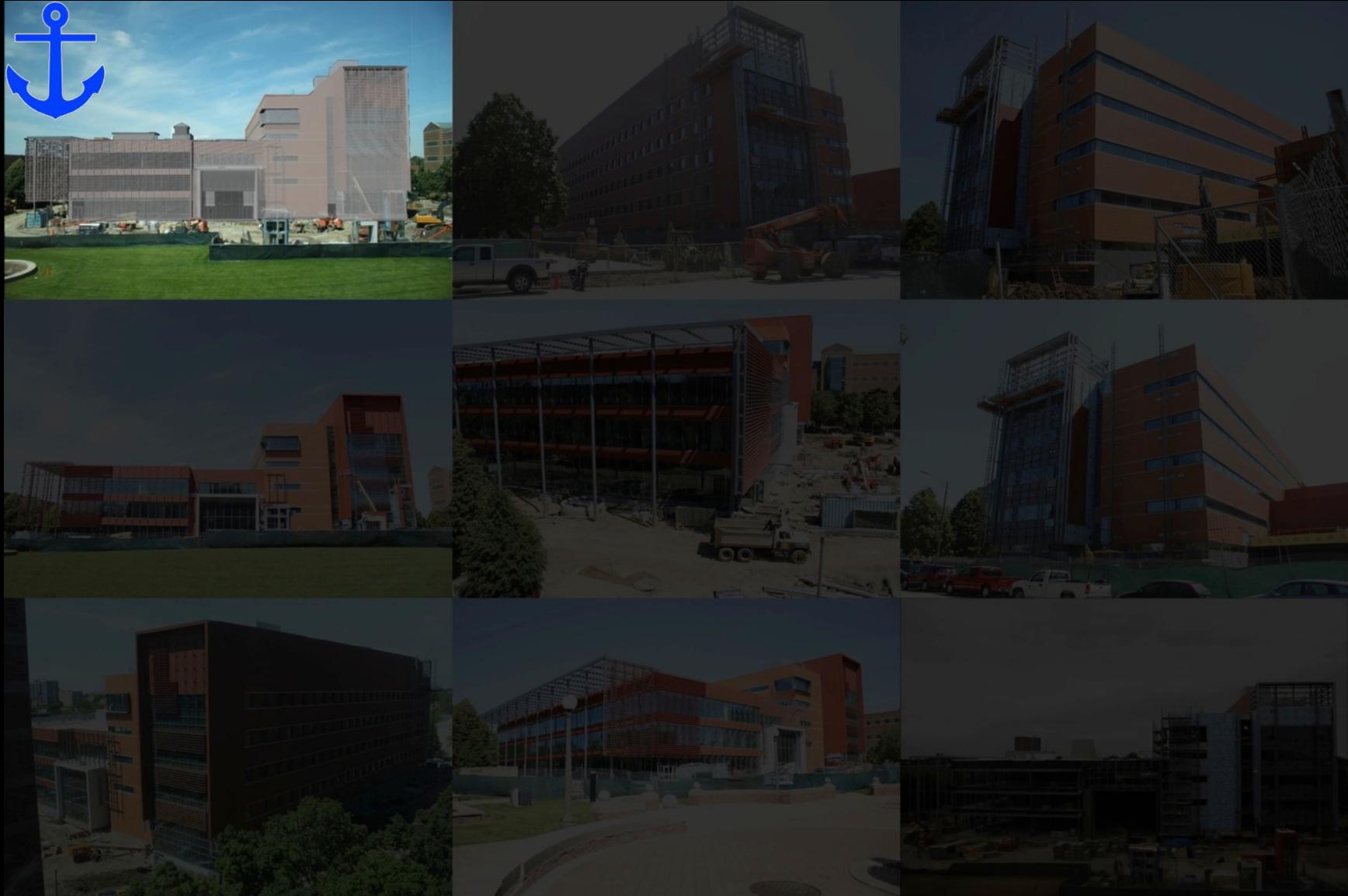
Model-assisted Structure-from-Motion



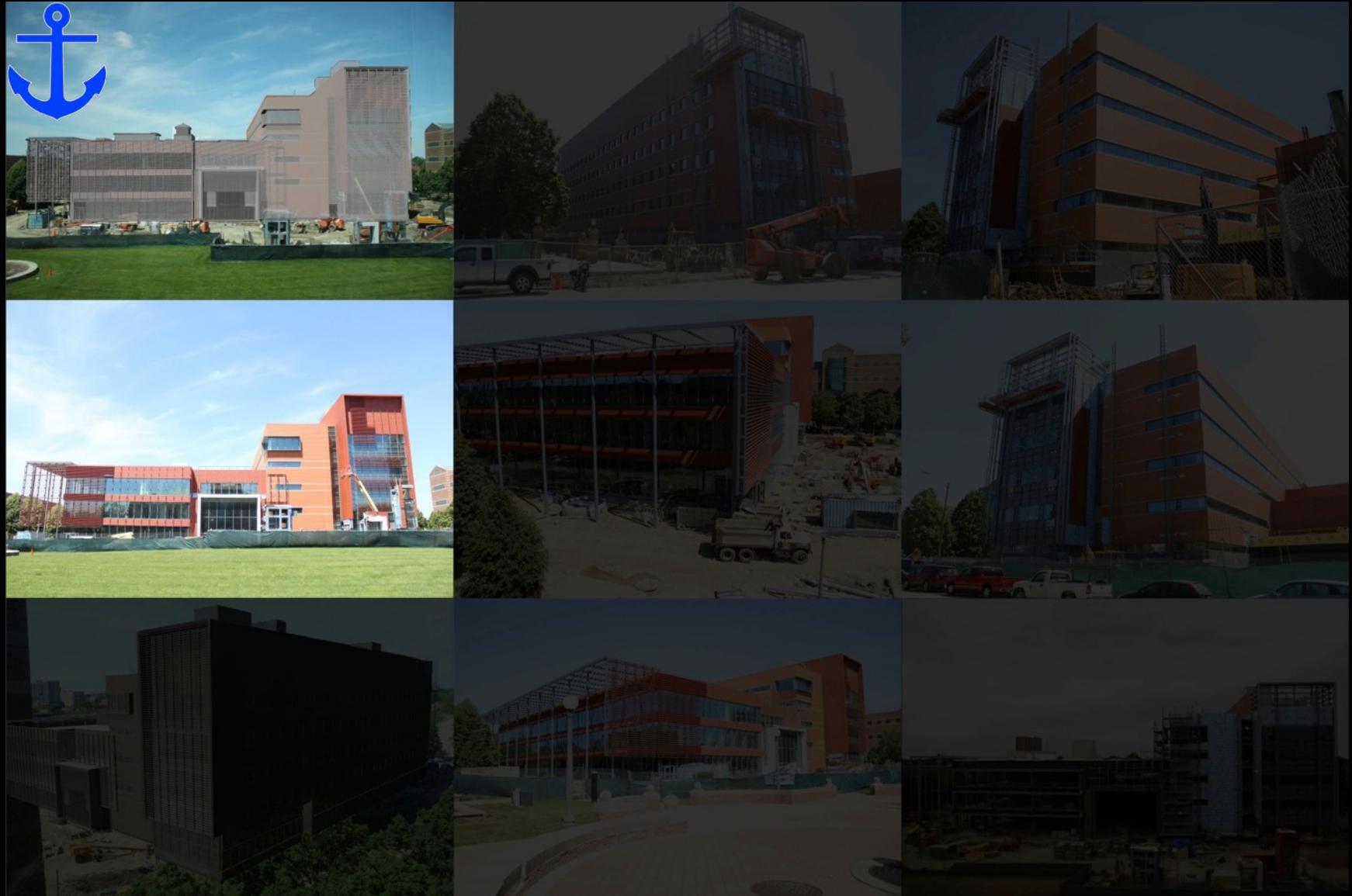
Model-assisted Structure-from-Motion



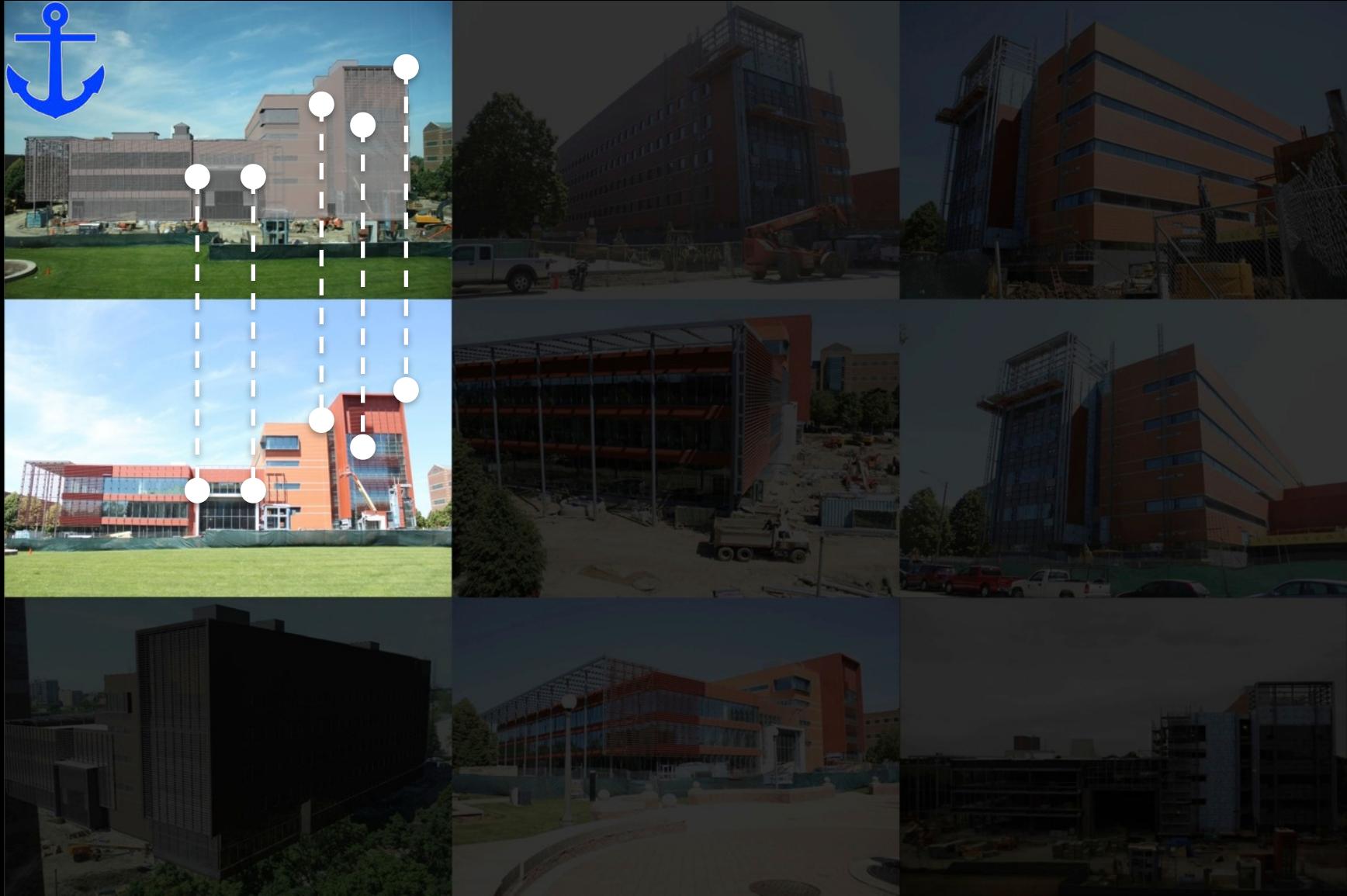
Model-assisted Structure-from-Motion



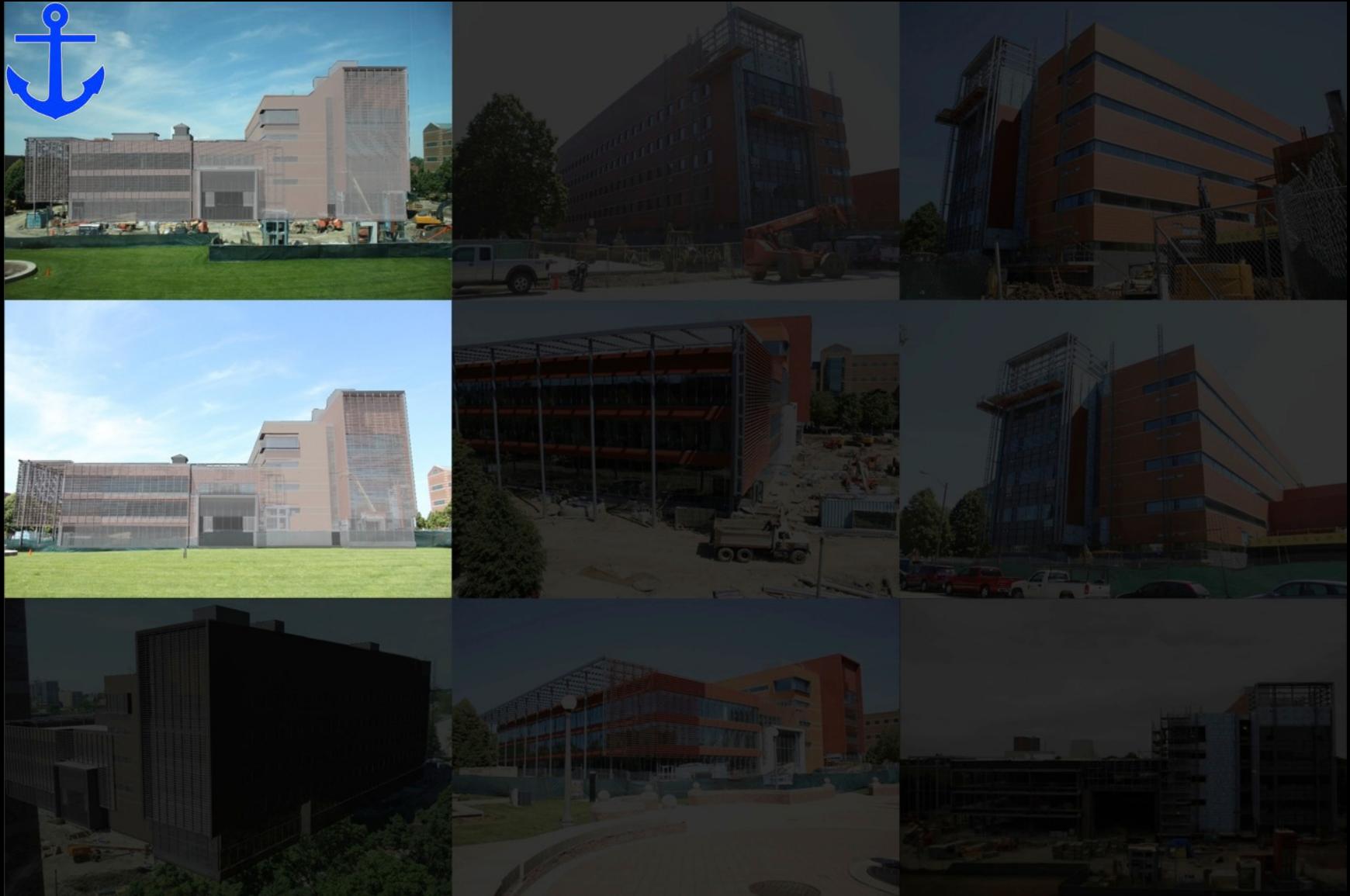
Model-assisted Structure-from-Motion



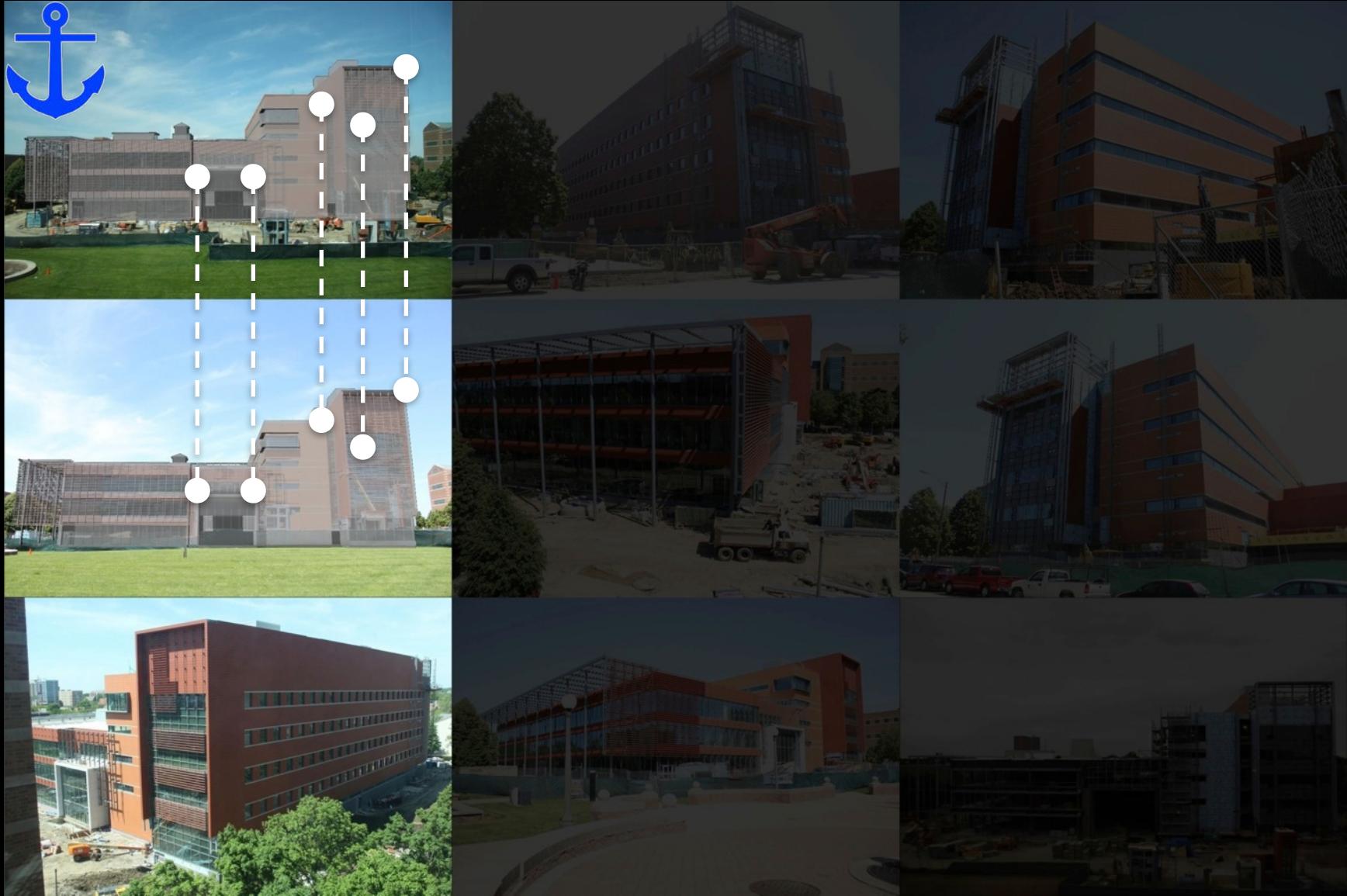
Model-assisted Structure-from-Motion



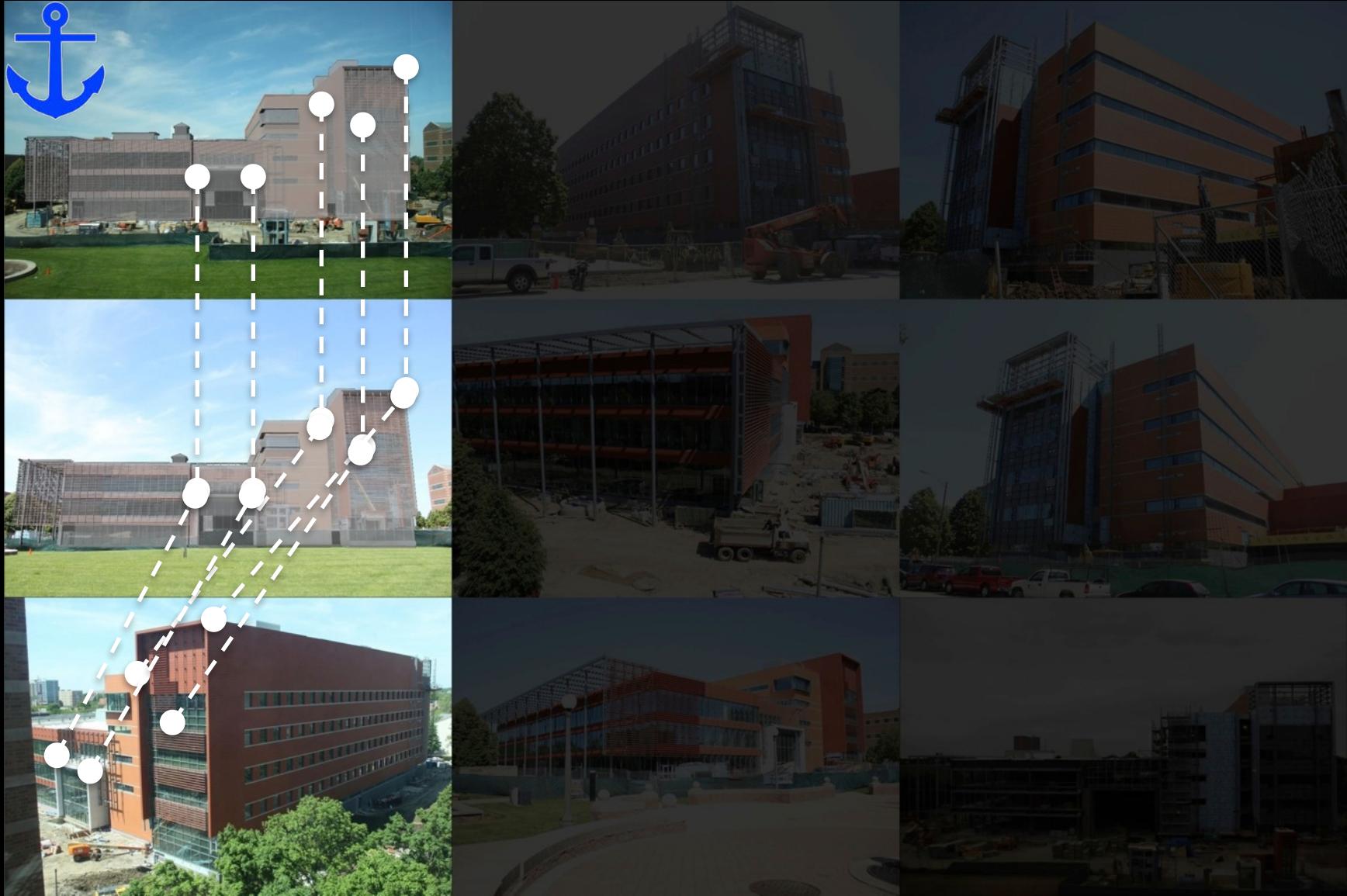
Model-assisted Structure-from-Motion



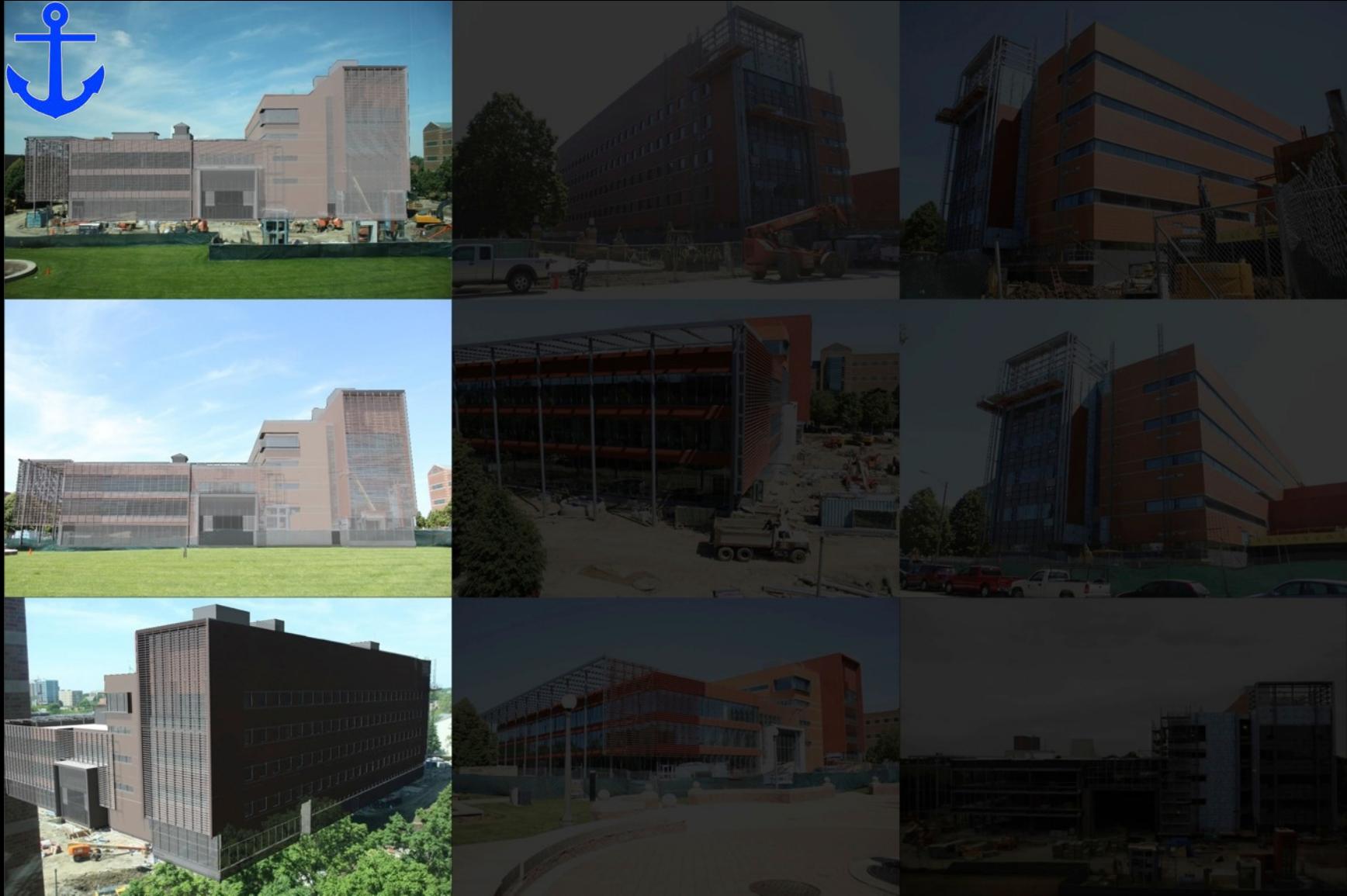
Model-assisted Structure-from-Motion



Model-assisted Structure-from-Motion



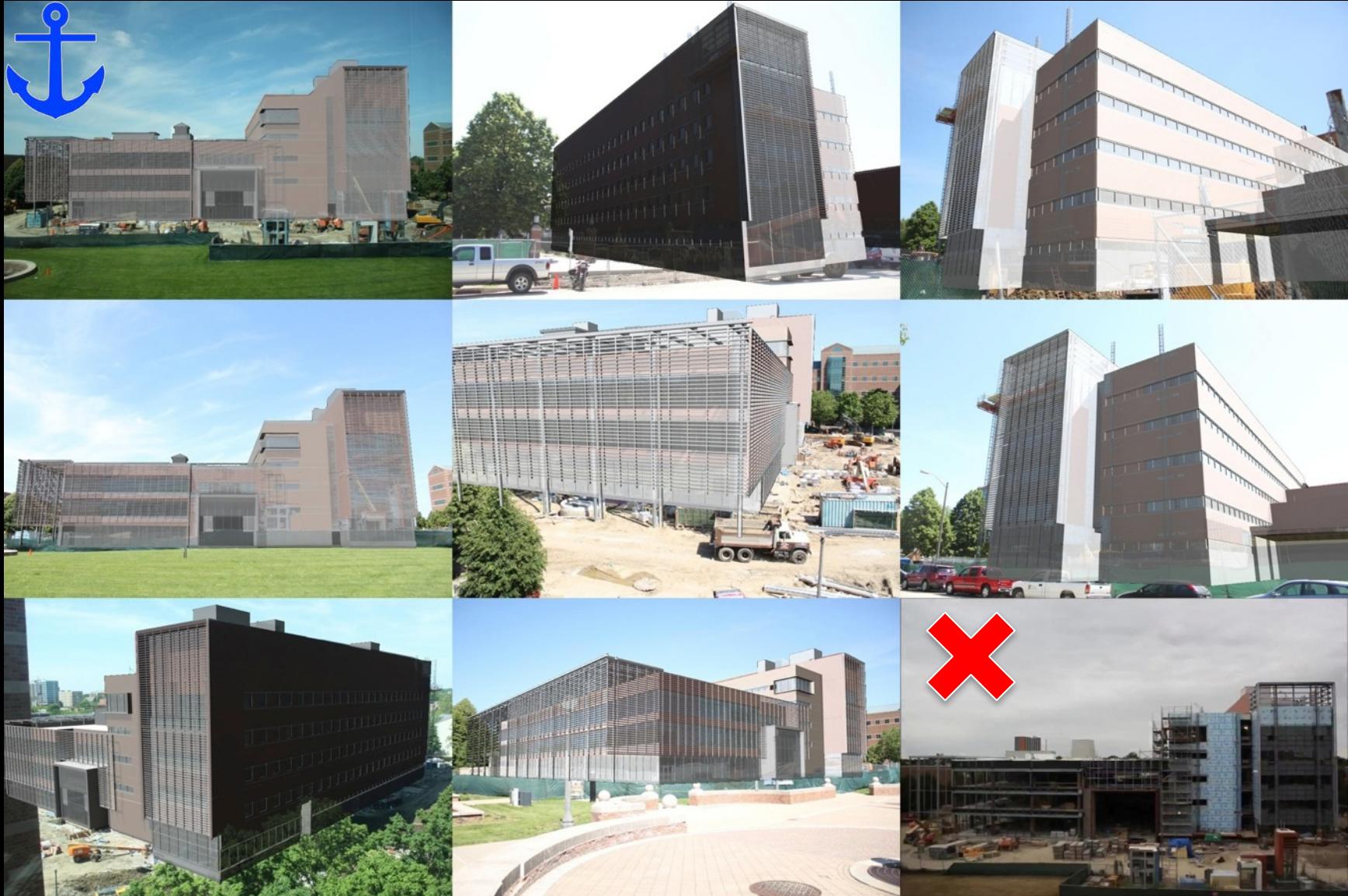
Model-assisted Structure-from-Motion



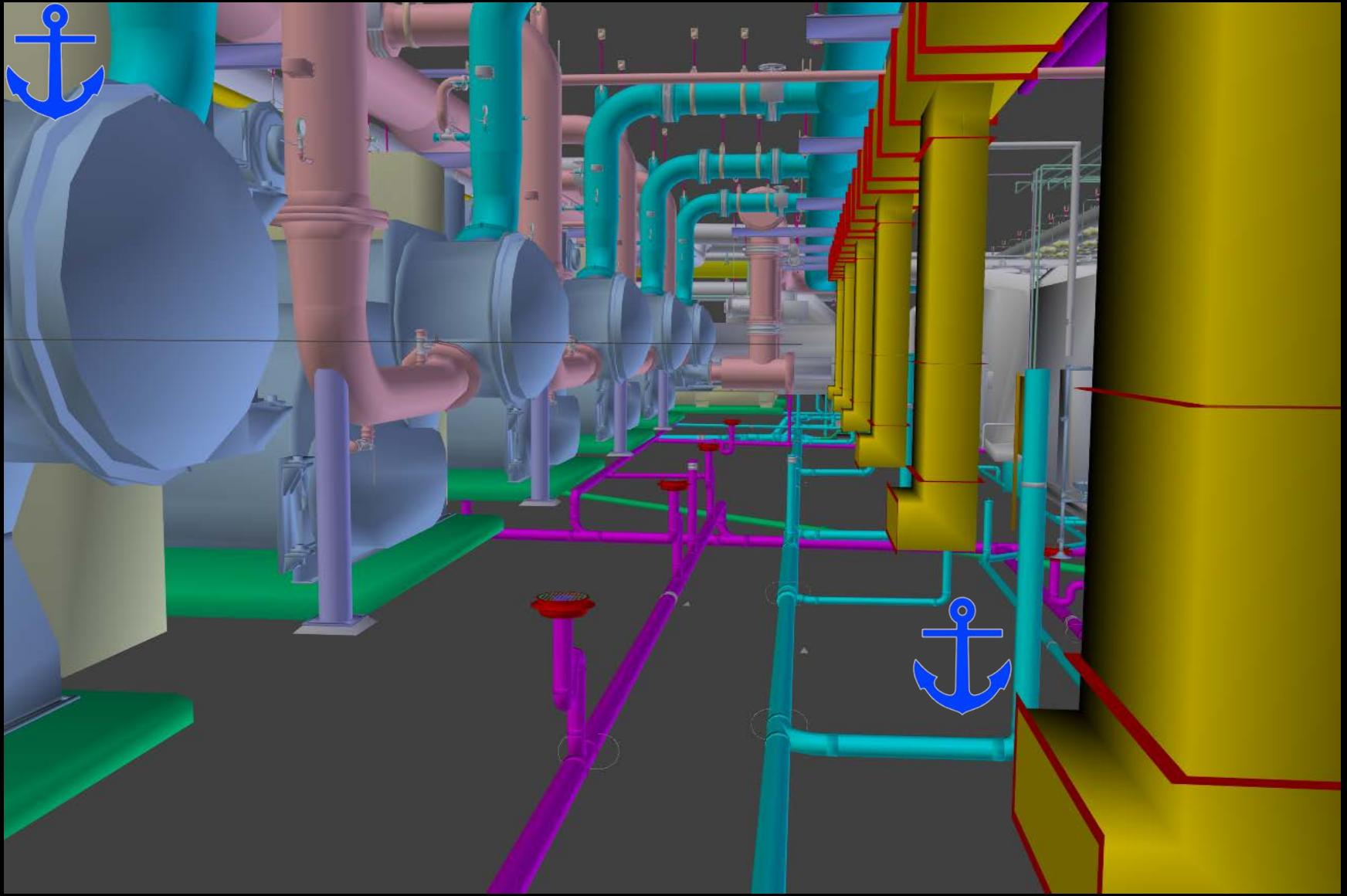
Model-assisted Structure-from-Motion



Model-assisted Structure-from-Motion



Model-assisted Structure-from-Motion

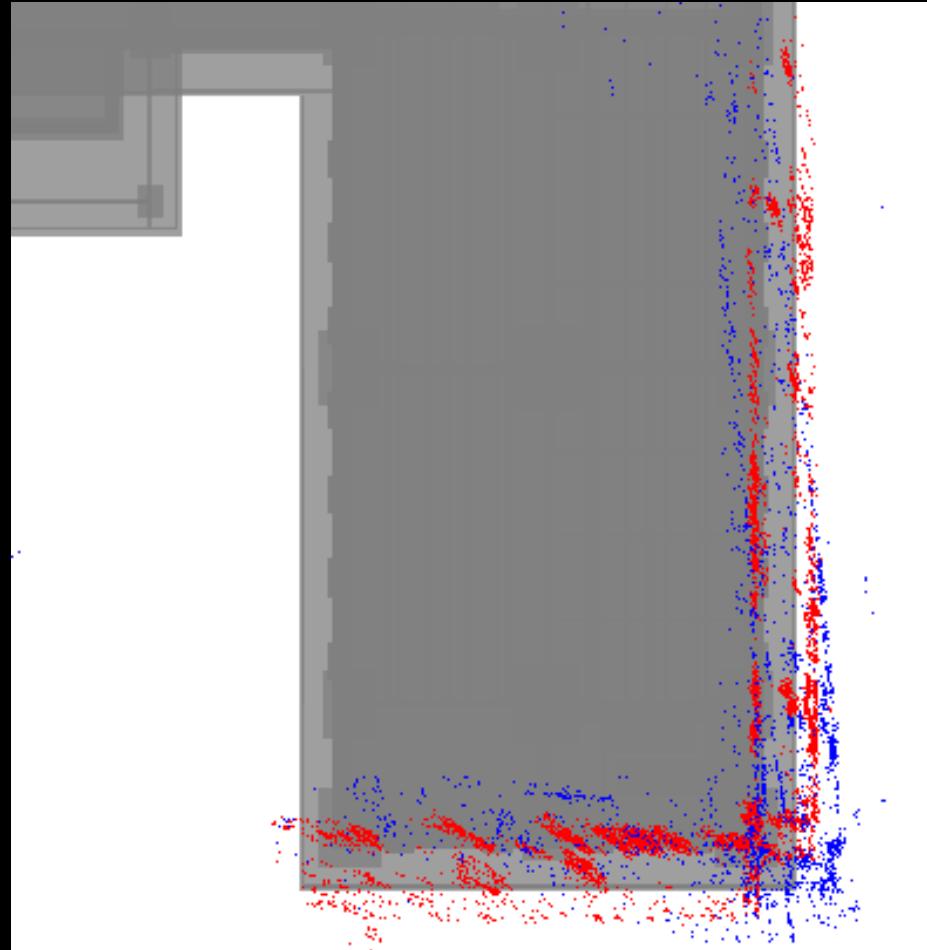


Comparisons to Existing SfM Methods

	Construction datasets		Middlebury datasets	
	Ours	Photosynth*	Ours	Photosynth*
Rotation error (degrees)	0.74	4.23	2.47	3.31
Translation error (meters)	0.50	2.18	0.06	0.19

* <https://code.google.com/p/visual-experiments/>

Comparisons to Existing SfM Methods

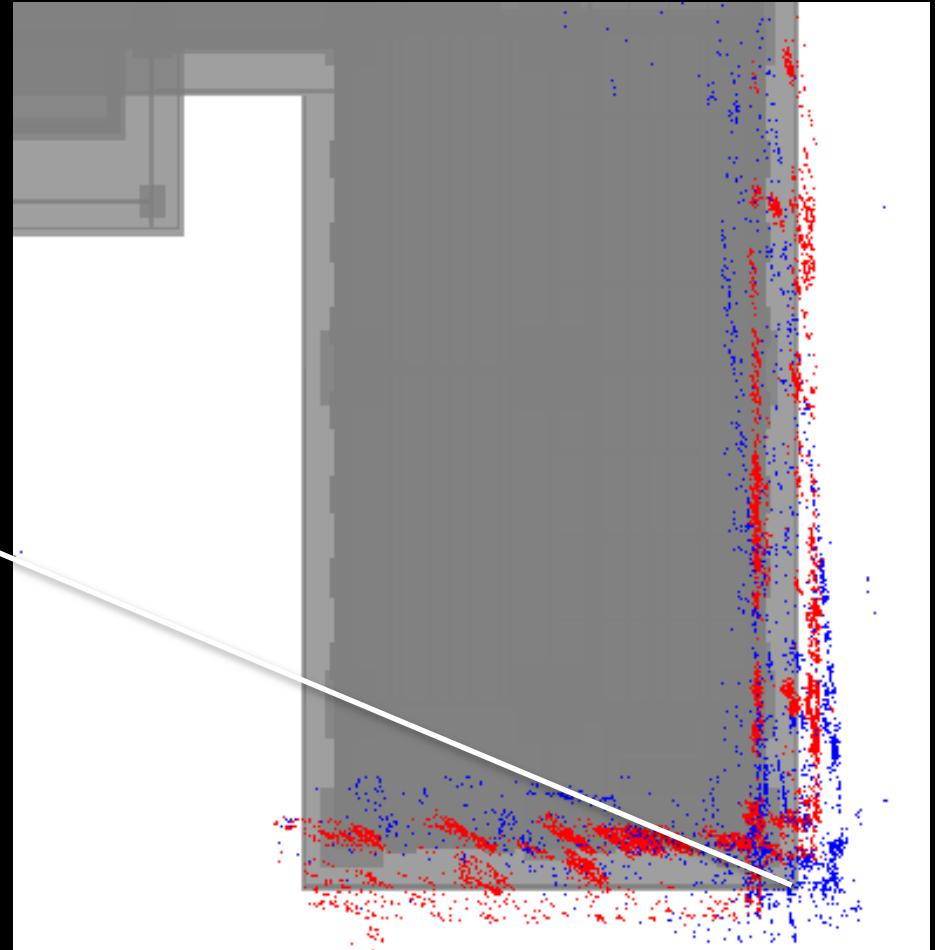


Visual SfM* reconstruction
Our reconstruction

Constraints help prevent drift

*[Wu et al. 2011, 2013]

Comparisons to Existing SfM Methods



Visual SfM* reconstruction
Our reconstruction

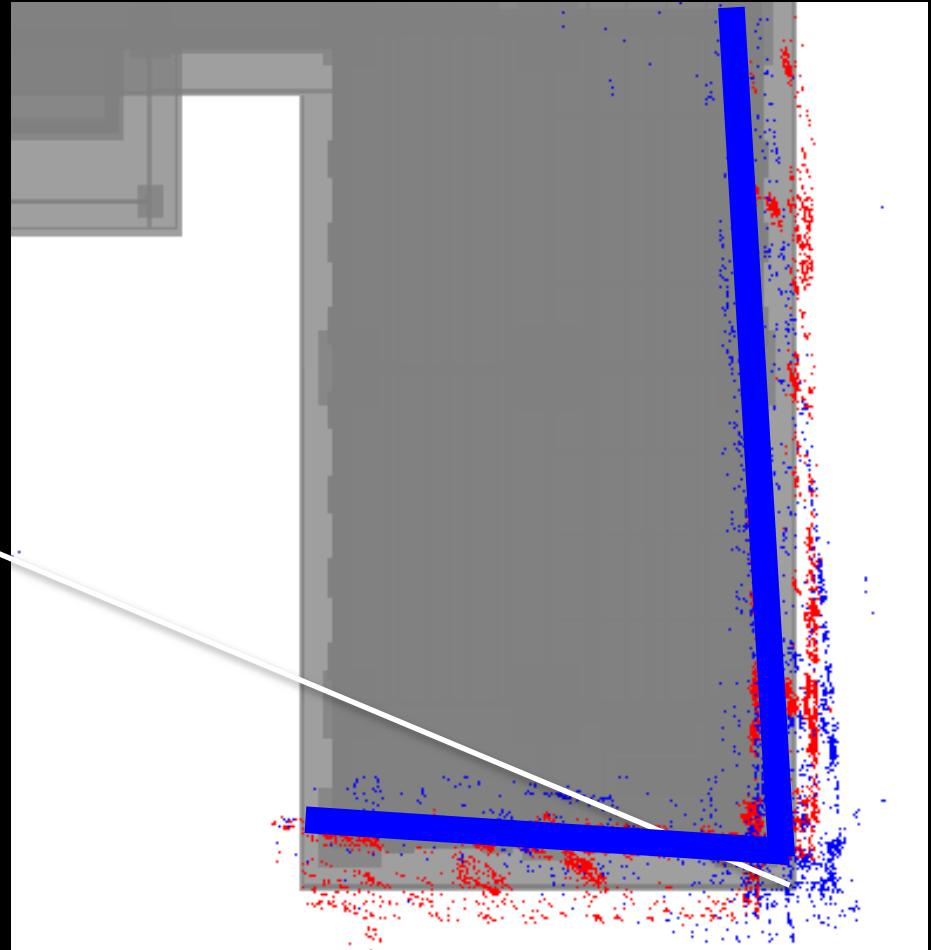
Constraints help prevent drift

*[Wu et al. 2011, 2013]

Comparisons to Existing SfM Methods



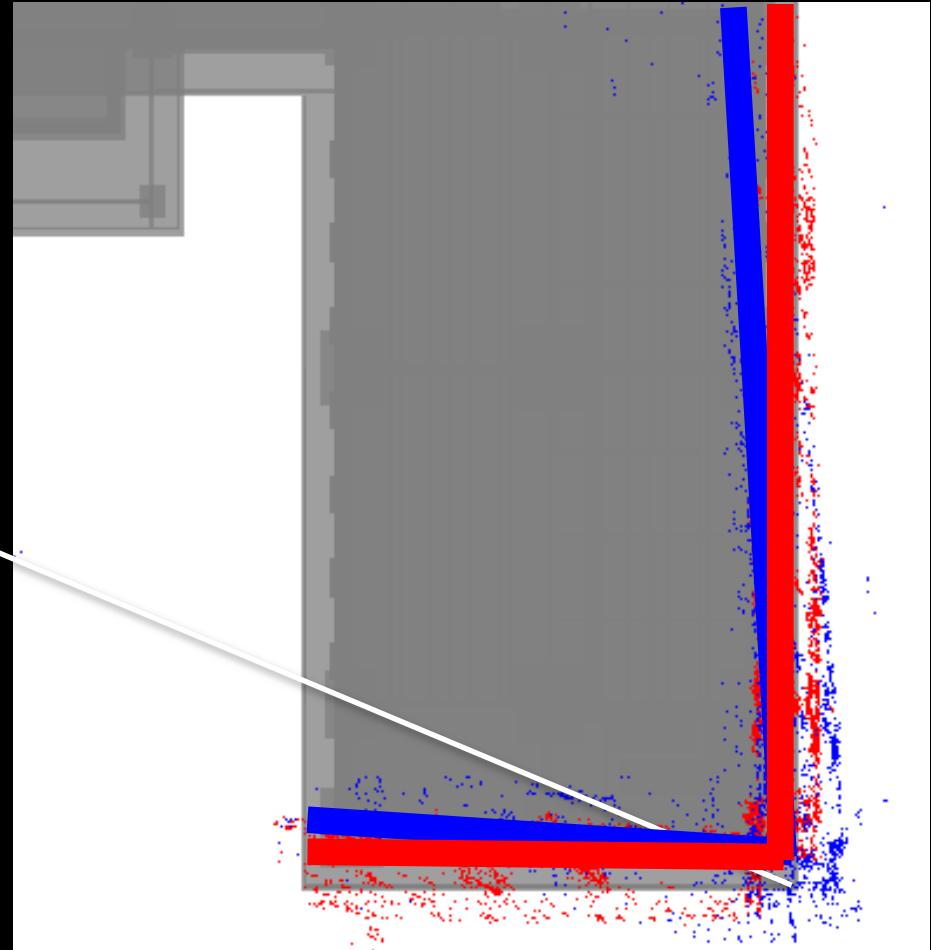
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Comparisons to Existing SfM Methods



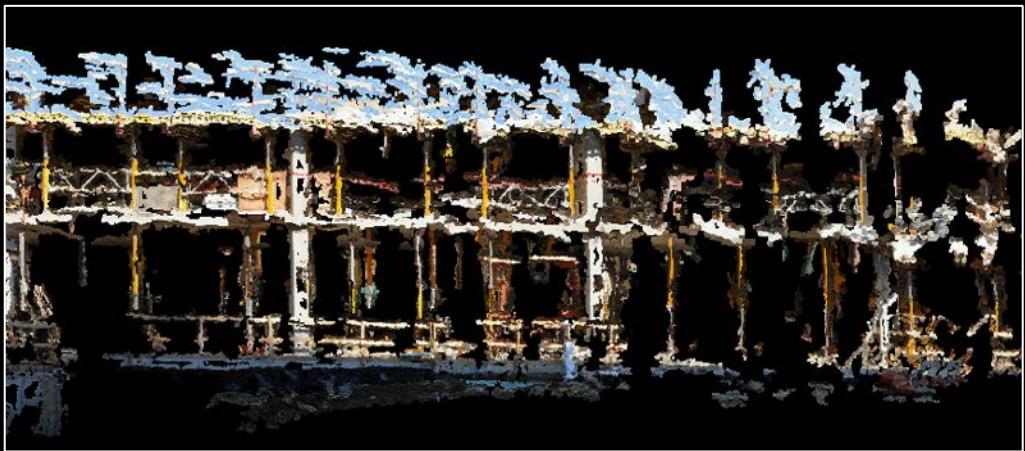
Visual SfM* reconstruction
Our reconstruction

Constraints help prevent drift

*[Wu et al. 2011, 2013]

Comparisons to Existing SfM Methods

Our reconstruction



Visual SfM reconstruction



More accurate and complete reconstructions

ConstructAide Preprocessing

- Creating 4D image sequences
 - Easy if time-lapse data exists
 - Possible otherwise
- Detecting occlusions
 - Static and dynamic occlusions handled differently
- Extract rendering information from BIM

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ConstructAide Preprocessing

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Unordered Image Sets to Time-lapses



Unordered Image Sets to Time-lapses



Before time-lapse conversion

Unordered Image Sets to Time-lapses



Unordered Image Sets to Time-lapses



Before time-lapse conversion

Unordered Image Sets to Time-lapses



After time-lapse conversion

Unordered Image Sets to Time-lapses



Unordered Image Sets to Time-lapses



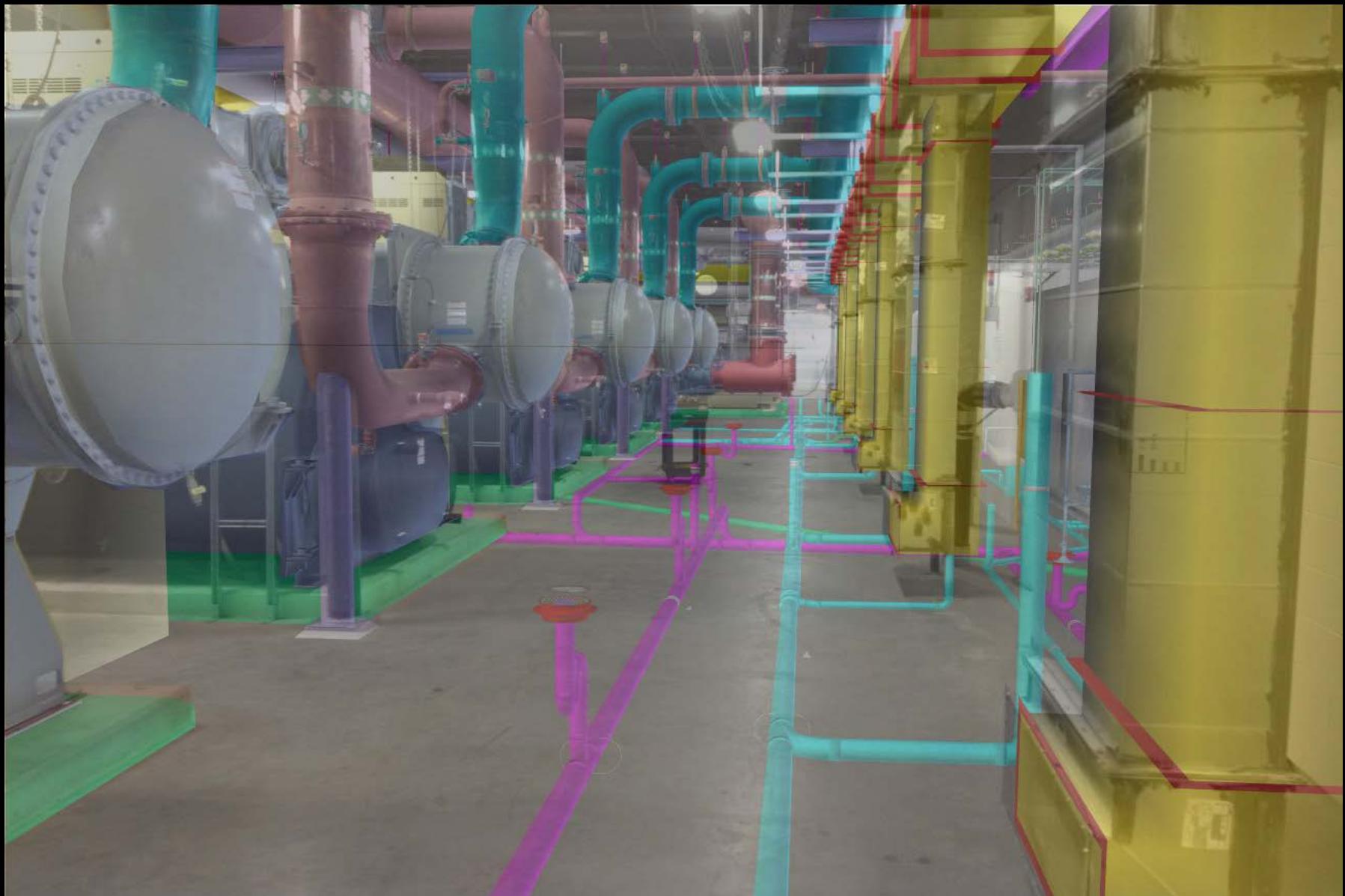
Unordered Image Sets to Time-lapses



Detecting Static Occlusions



Detecting Static Occlusions

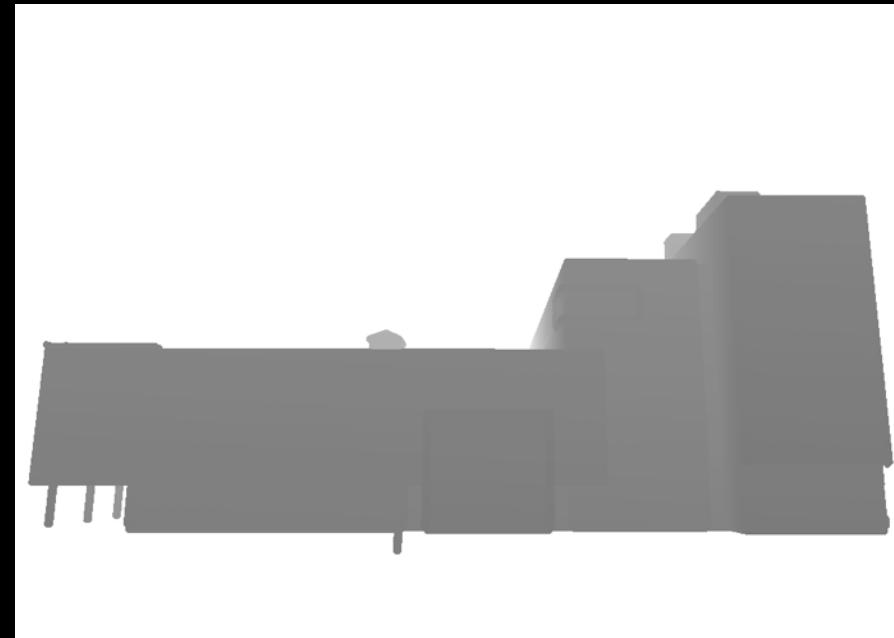


Detecting Static Occlusions

SfM point cloud



Mesh



- 1) Compare mesh and point cloud geometry
- 2) Keep points that deviate from mesh values
- 3) Smooth remaining points based on image

Detecting Static Occlusions

Remaining points



- 1) Compare mesh and point cloud geometry
- 2) Keep points that deviate from mesh values
- 3) Smooth remaining points based on image

Detecting Static Occlusions

Smoothed points



- 1) Compare mesh and point cloud geometry
- 2) Keep points that deviate from mesh values
- 3) Smooth remaining points based on image

Detecting Static Occlusions



Detecting Static Occlusions



Detecting Static Occlusions



Detecting Dynamic Occlusions



Input A



Input B

Detecting Dynamic Occlusions



Input A



Aligned Input B

Detecting Dynamic Occlusions

Occlusion probabilities

Detecting Dynamic Occlusions



Detecting Dynamic Occlusions



Detecting Dynamic Occlusions



Putting BIM to Work

- BIM data contains
 - Per-element material information
 - GPS and timing data
- From this we synthesize
 - Mesh component hierarchy for user selection
 - Material models for off-the-shelf renderers
 - Lighting information

Selection Tools



Selection Tools



Selection Tools



Performance Monitoring



Selection brush mode: Element

Scheduling:

behind ahead

Build deviations:

no deviation significant deviation

4D navigation:

past future

Go to left cam Go to right cam

Architectural rendering:

Create preview rendering Create physical rendering

Automatic occlusion estimation:

Calculate static occlusions Calculate dynamic occlusions

Building element notes:

Performance Monitoring



Selection brush mode: Element

Scheduling:

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no deviation significant deviation

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past future

Go to left cam Go to right cam

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Calculate static occlusions Calculate dynamic occlusions

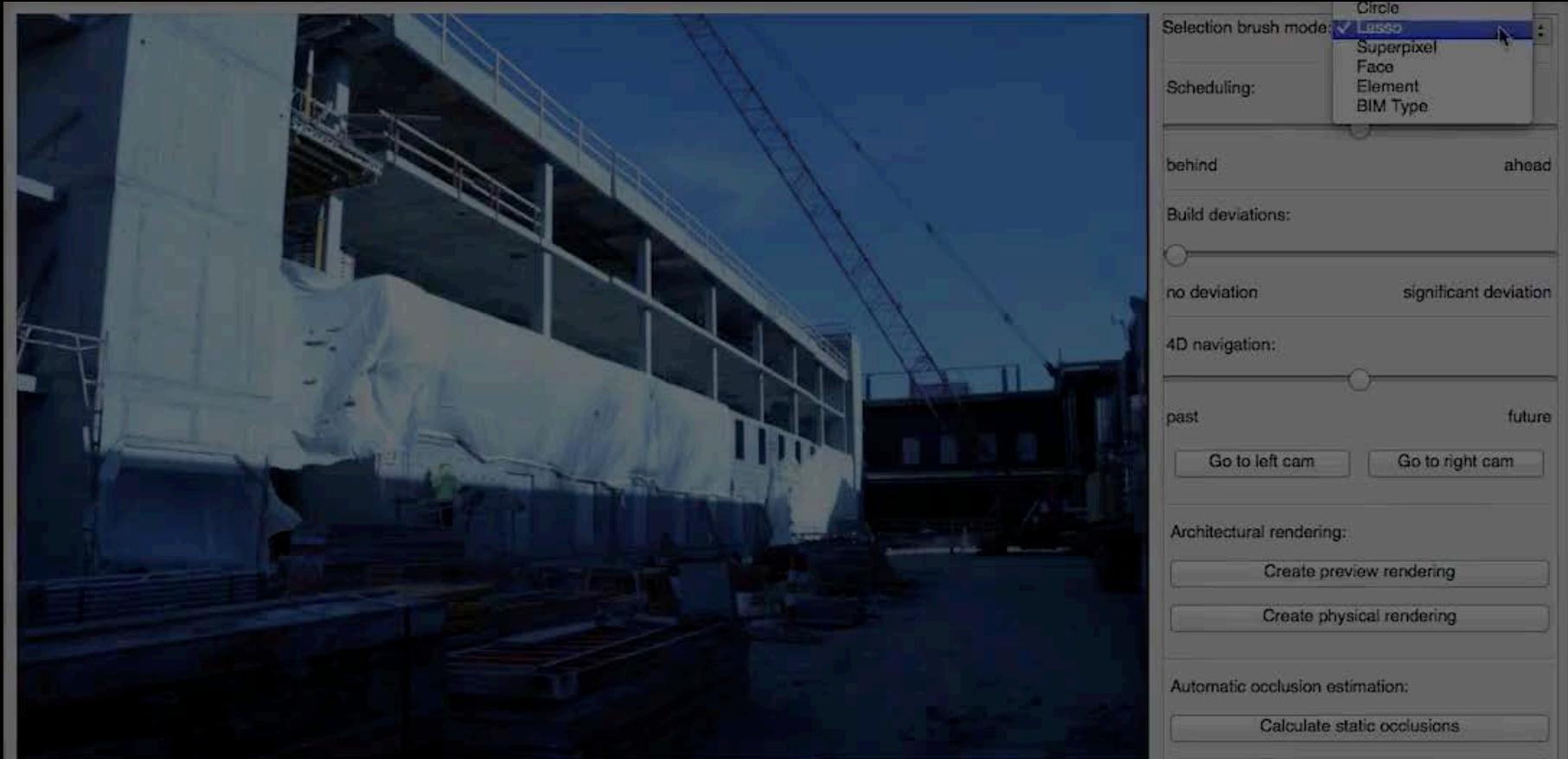
Building element notes:

Querying Previous/Future Information



4D Navigation

Querying Previous/Future Information



4D Navigation

Querying Previous/Future Information



4D Navigation

Querying Previous/Future Information



The image shows a 3D rendering of a modern building's exterior. A large blue circular selection brush is positioned over a section of the building's facade, centered on a glass-enclosed entrance. The software interface on the right side of the screen includes the following controls and information:

- Selection brush mode:** Circle (selected)
- Scheduling:** A horizontal slider with endpoints "behind" and "ahead".
- Build deviations:** A horizontal slider with endpoints "no deviation" and "significant deviation".
- 4D navigation:** A horizontal slider with endpoints "past" and "future".
- Cameras:** Buttons for "Go to left cam" and "Go to right cam".
- Architectural rendering:**
 - Create preview rendering
 - Create physical rendering
- Automatic occlusion estimation:**
 - Calculate static occlusions
 - Calculate dynamic occlusions
- Building element notes:** An empty text input field.

4D Navigation

Querying Previous/Future Information



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4D Navigation

Querying Previous/Future Information



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- Automatic occlusion estimation:**
 - Calculate static occlusions
 - Calculate dynamic occlusions
- Building element notes:** An empty text input field.

4D Navigation

Modifying Occluding Segments



Modifying Occluding Segments



Modifying Occluding Segments



Modifying Occluding Segments



Modifying Occluding Segments



Modifying Occluding Segments



Modifying Occluding Segments



Modifying Occluding Segments



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 - Lighting information

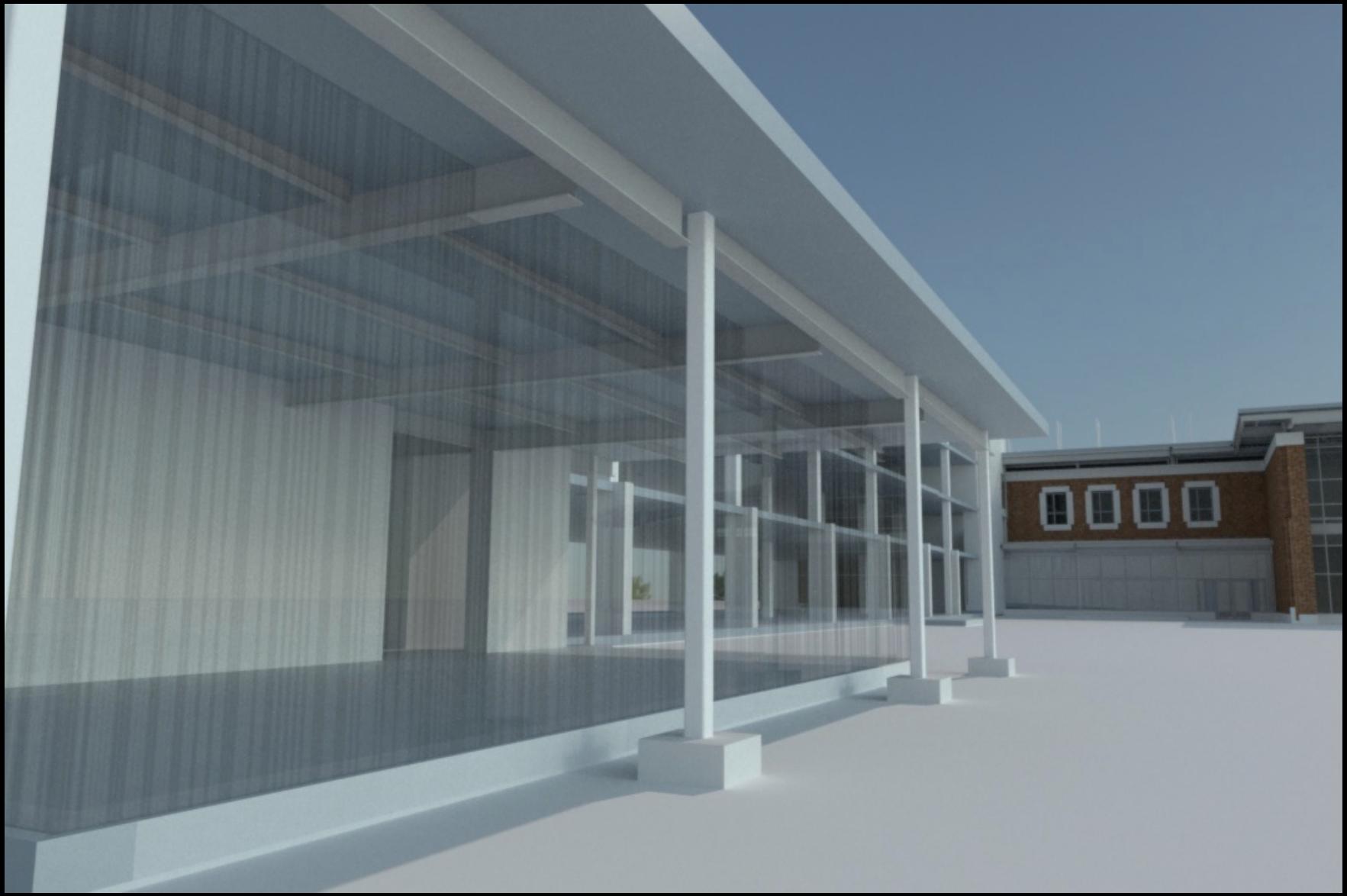
Putting BIM to Work

- BIM data contains
 - Per-element material information
 - GPS and timing data
- From this we synthesize
 - Mesh component hierarchy for user selection
 - Material models for off-the-shelf renderers
 - Lighting information

Architectural Visualization



Architectural Visualization



Architectural Visualization



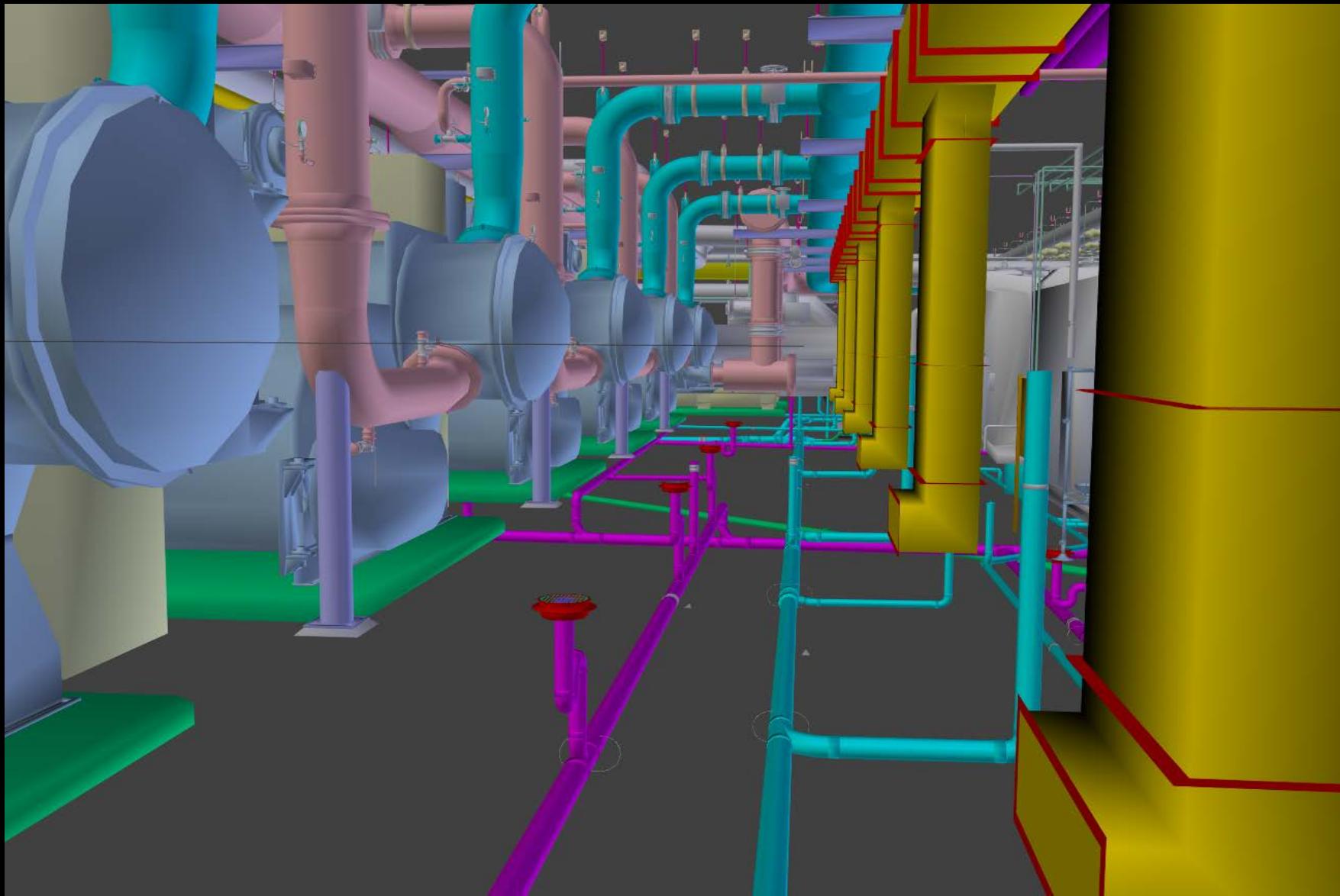
Architectural Visualization



Architectural Visualization



Architectural Visualization











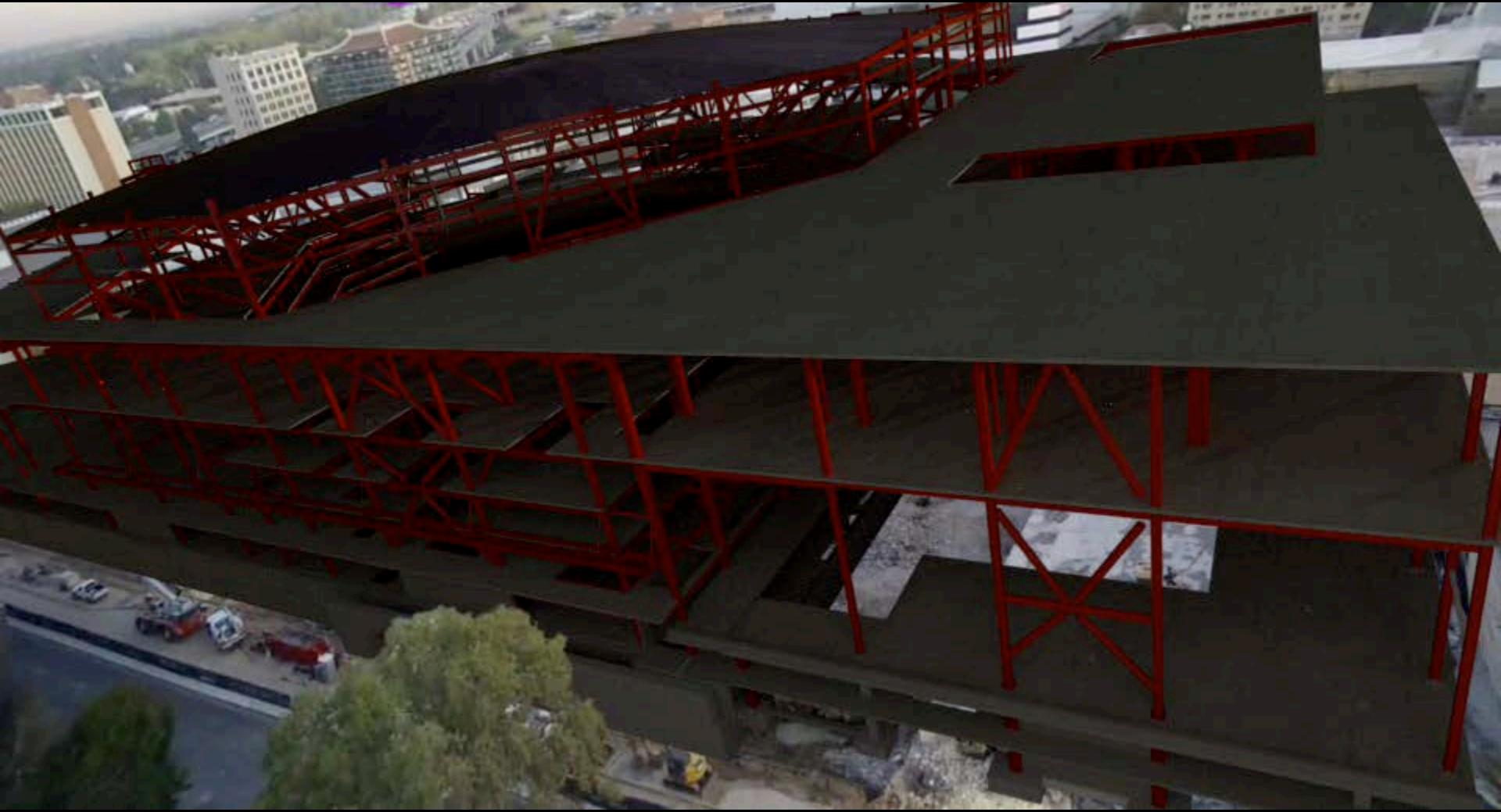


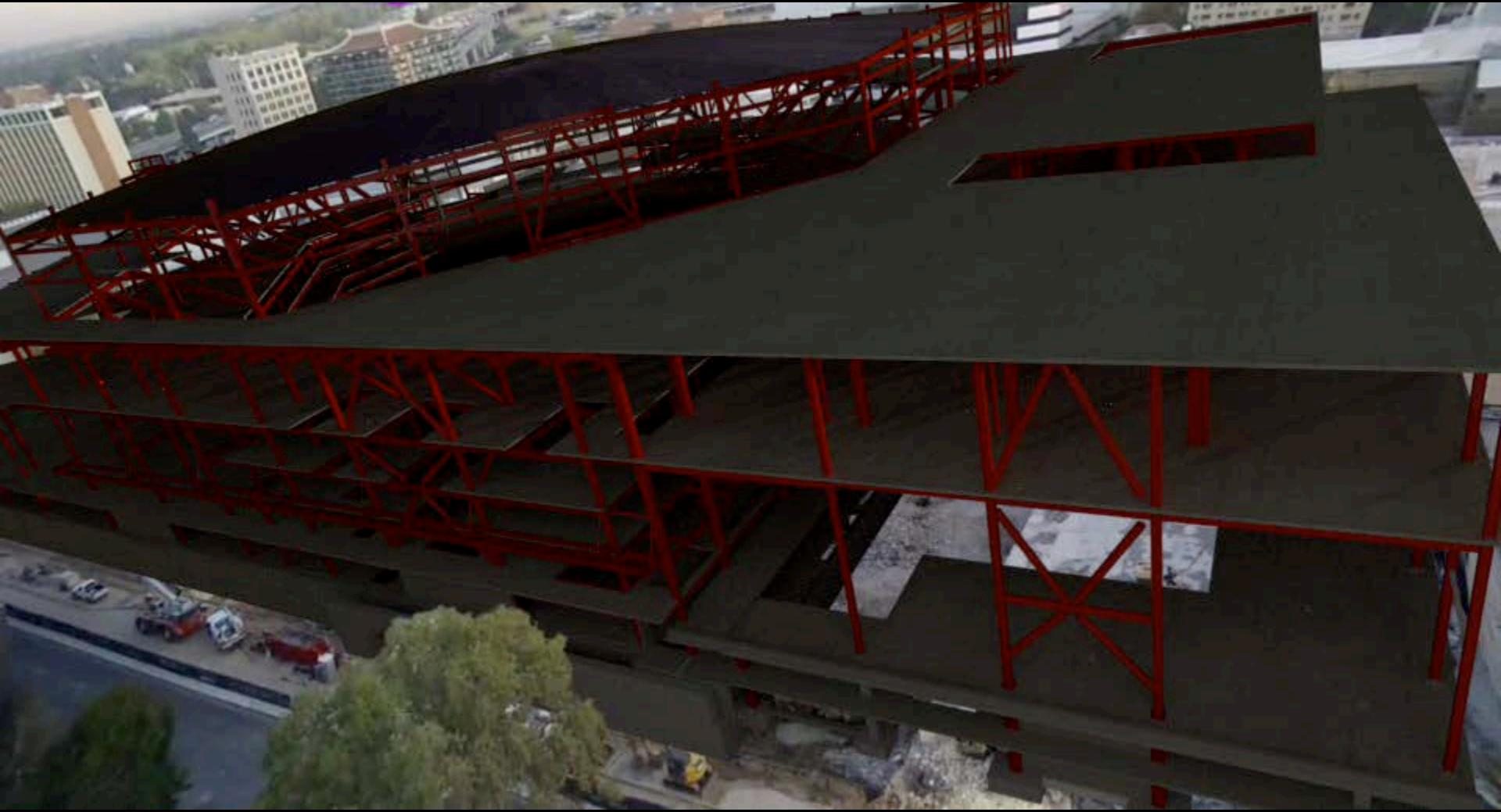














Material Selection and Adjustment



Material Selection and Adjustment



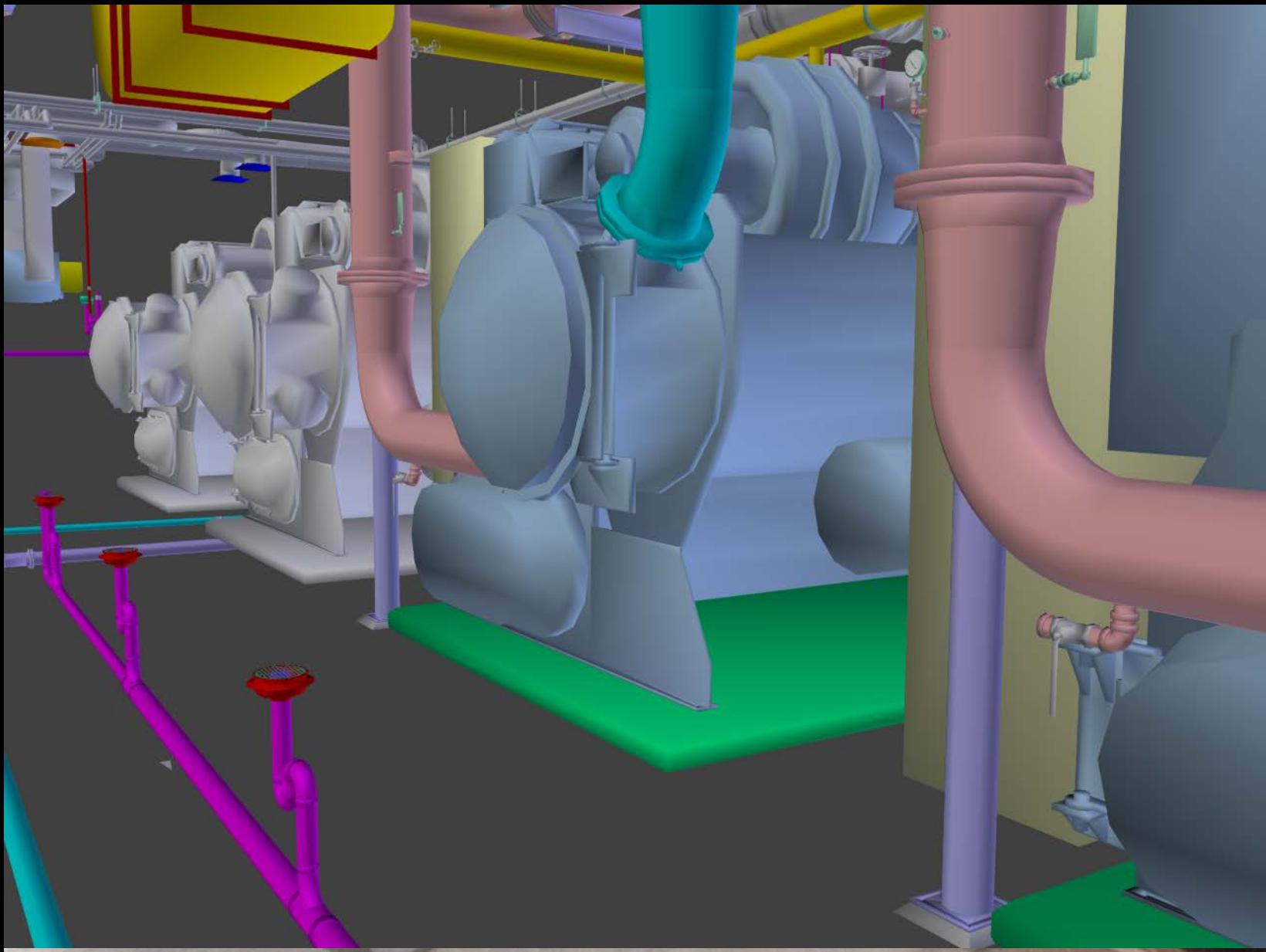
Material Selection and Adjustment



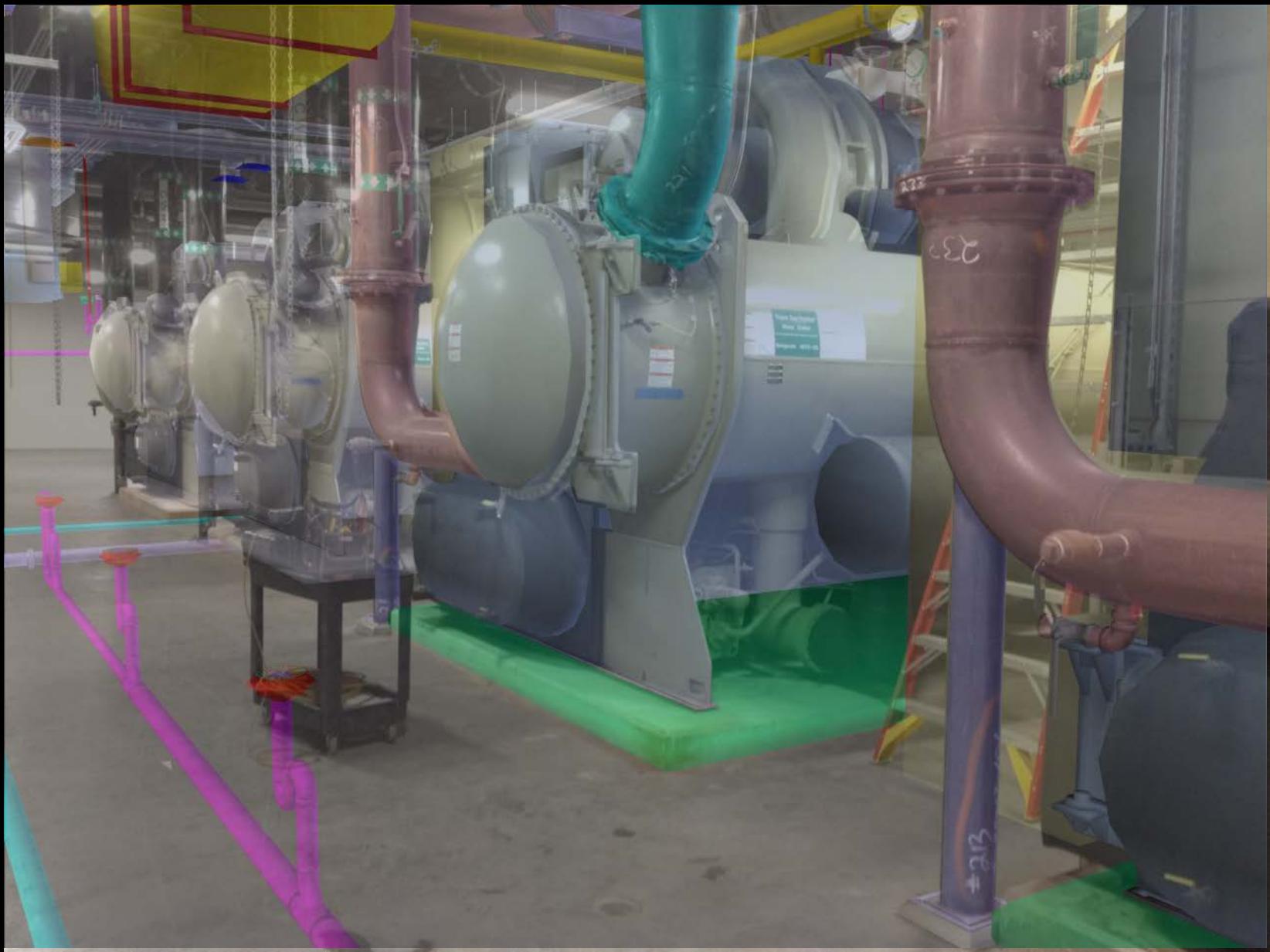
Indoor Results



Indoor Results



Indoor Results



Aerial Results



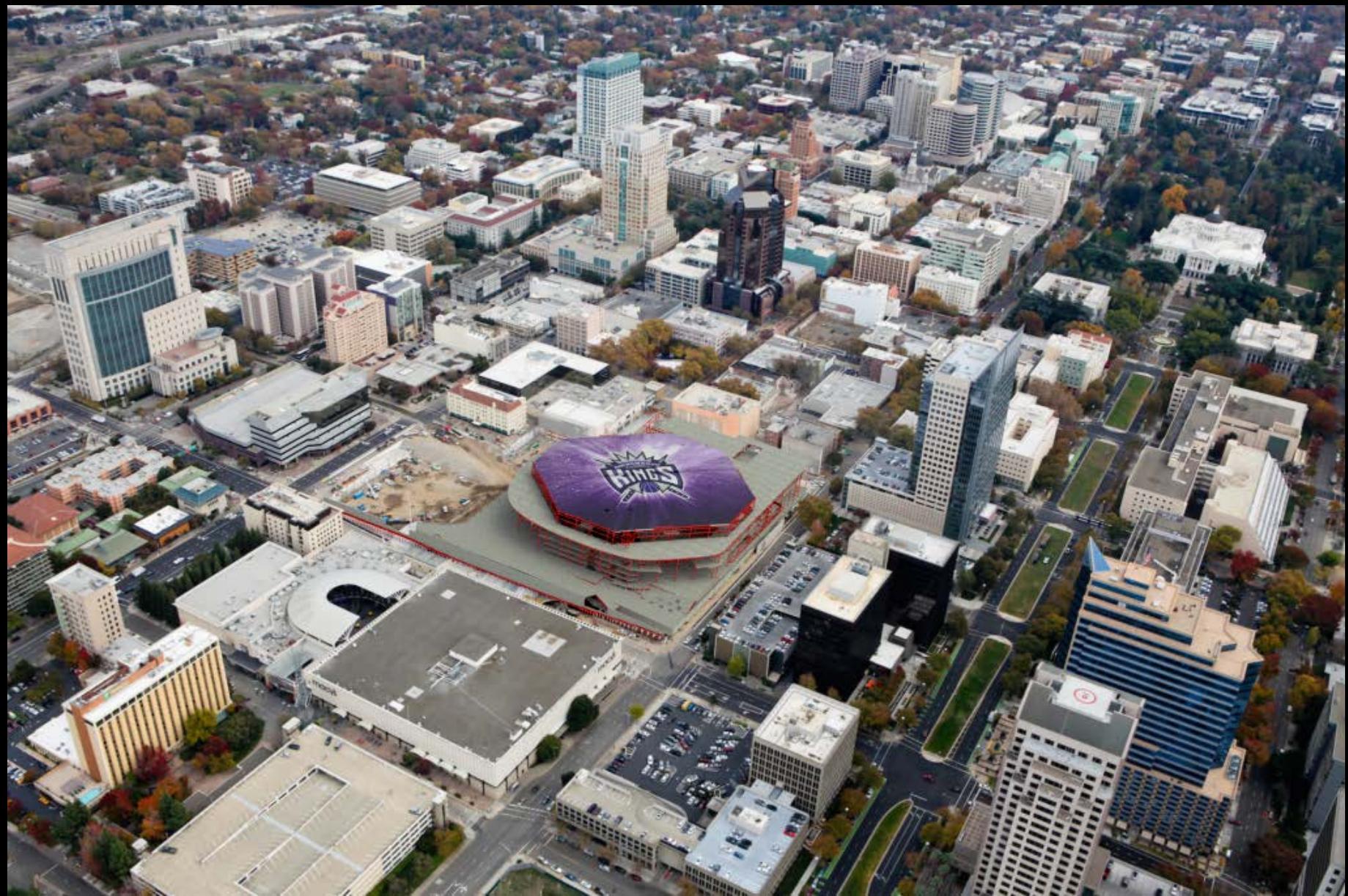
Aerial Results



Aerial Results



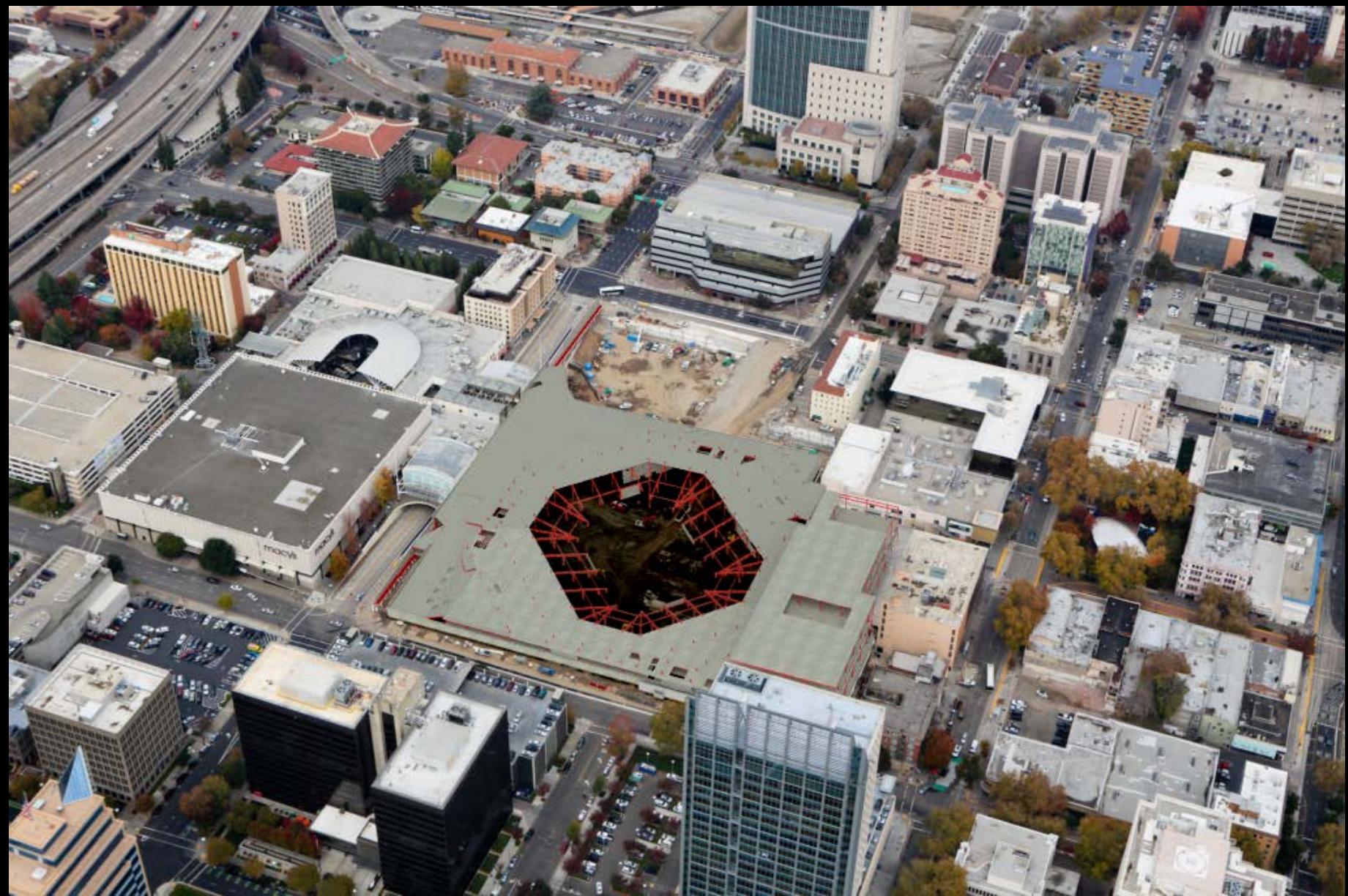
Aerial Results



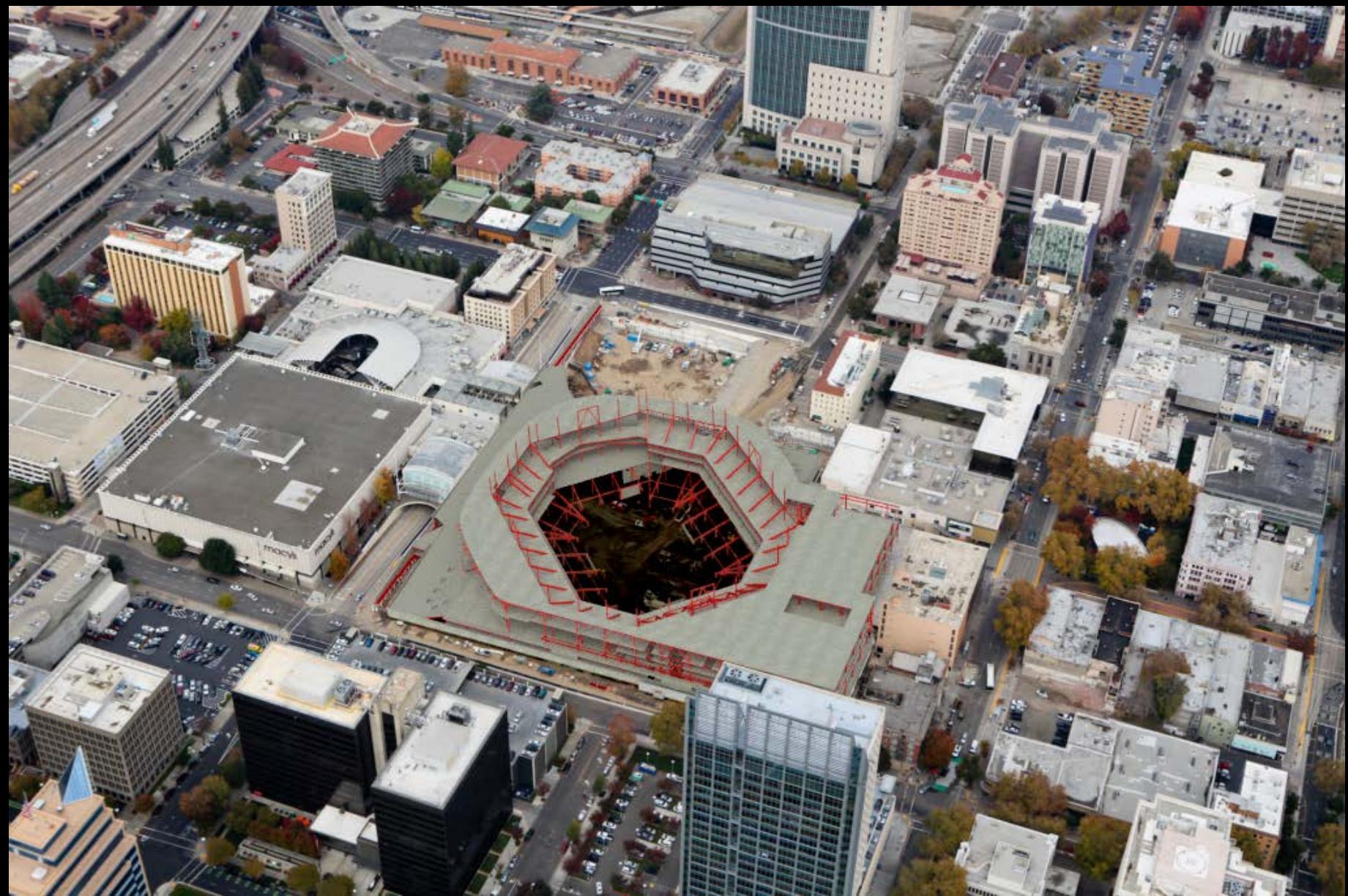
Aerial Results



Aerial Results



Aerial Results

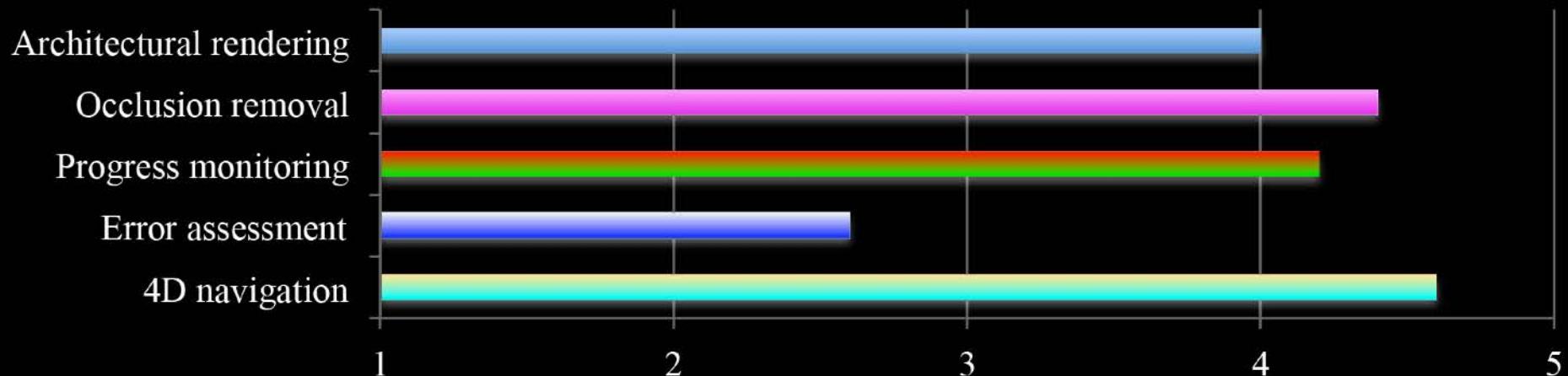


Aerial Results



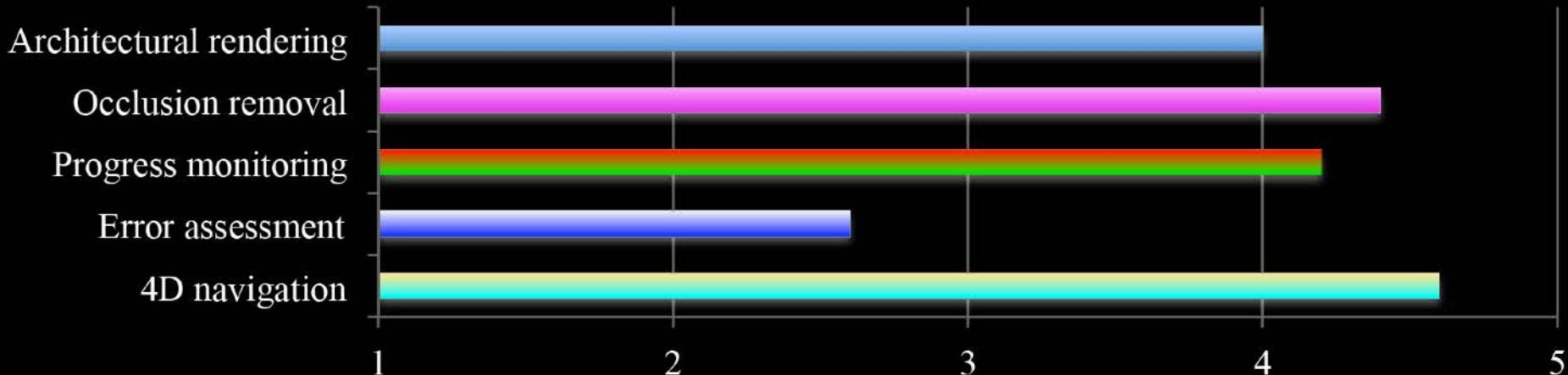
Domain Expert Responses

“Rate the usefulness of the following tools” (Likert scale, 5 = excellent)



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“Rate the usefulness of the following tools” (Likert scale, 5 = excellent)



Quotes from users:

- “Existing methods are highly subjective and based on judgment and experience”
- “Space-time navigation is very useful for assessing/verifying contractor claims.”
- “Automatic progress and error assessment would be nice.”

Recap

- ConstructAide facilitates everyday construction monitoring tasks
 - 4D navigation through photos
 - Architectural visualization
 - Progress and performance monitoring
- Rendering, occlusion, and time-lapse information are synthesized automatically from BIM + photos
- Constrained SfM works well when user input is available

Future Work

- Mobile, real time implementation for field use
(in progress)
- Comprehensive user study
- How to better incorporate mesh in SfM?
 - Automatic registration [Aubry et al. 2014]

