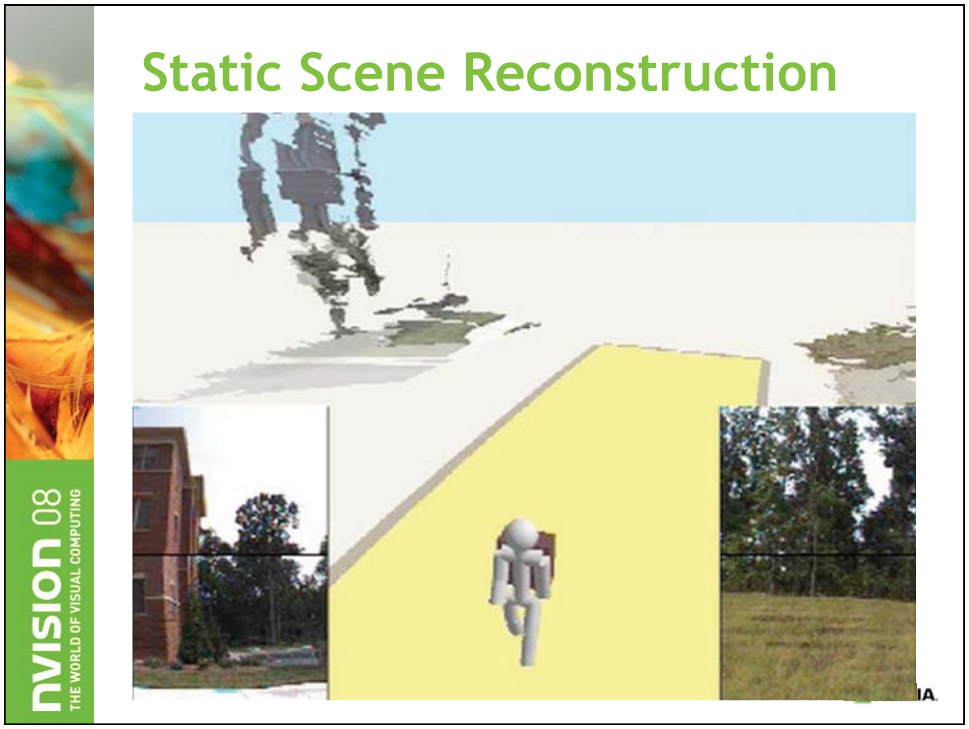

nVISION 08
THE WORLD OF VISUAL COMPUTING
GPU supported Real-Time Scene Reconstruction with a Single Camera
Jan-Michael Frahm, 3D Computer Vision group, University of North Carolina at Chapel Hill
NVIDIA


Static Scene Reconstruction
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Capture on campus & in downtown Chapel Hill

2x4 cameras,
1024x768@30Hz

GPS location &
orientation

~$(400 GPUs)

- Chapel Hill (15-30mph, 30fps)
- **2.6M** frames (8 cams, 3 hours)
- **2 TB** video data

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Capture on campus & in downtown Chapel Hill

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Capture on campus & in downtown Chapel Hill

2x4 cameras,
1024x768@30Hz

GPS location &
orientation

~$(400 GPUs)

6 camera-head

GPS/Inertia sensors

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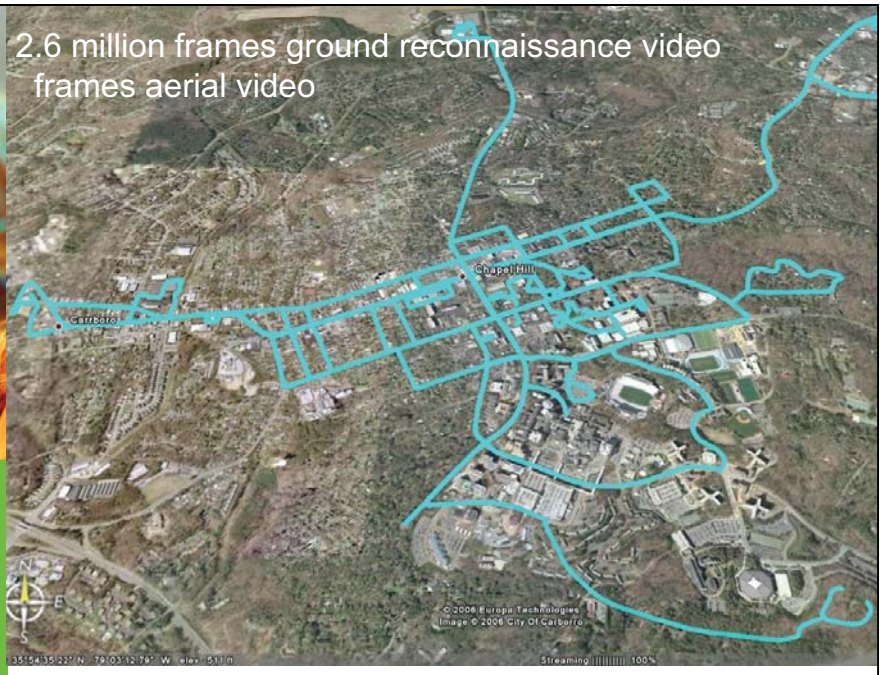
2.6 million frames ground reconnaissance video frames aerial video



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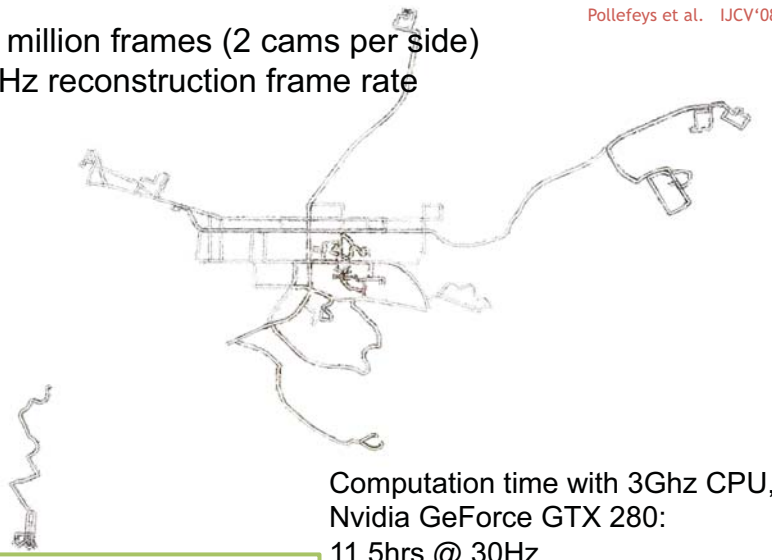
Pollefeys et al. IJCV'08

- 1.3 million frames (2 cams per side)
- 30 Hz reconstruction frame rate



Computation time with 3Ghz CPU, Nvidia GeForce GTX 280:
11.5hrs @ 30Hz
~2 weeks @ 1 Hz
~8 weeks @ 0.25 Hz

David Kirk:
Factor 100 is fundamentally different!

Speedup of ~120x

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3D Reconstruction Result

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3D model from video

Capture & 2D processing

3D model from video

Capture & 2D processing

images, 2D feature correspondences

3D model from video

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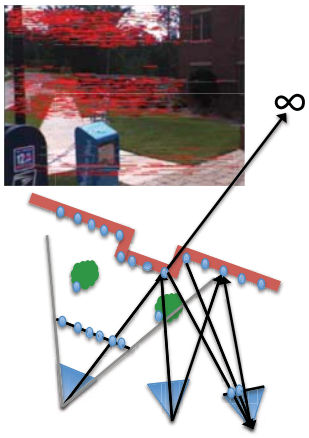
3D points & camera poses

images, camera poses



3D model from video

Capture & 2D processing

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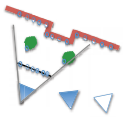
3D points & camera poses

images, camera poses



3D model from video

Capture & 2D processing

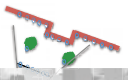
images, 2D feature correspondences

3D points & camera poses

images, camera poses

Dense 3D

images, camera poses, depth maps



The brighter the farther away

3D model from video

Capture & 2D processing

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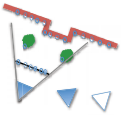
images, camera poses

Dense 3D

images, camera poses, depth maps

Model generation



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3D model from video

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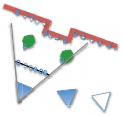

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GPU speedup ~190

GPU speedup ~140

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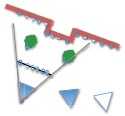

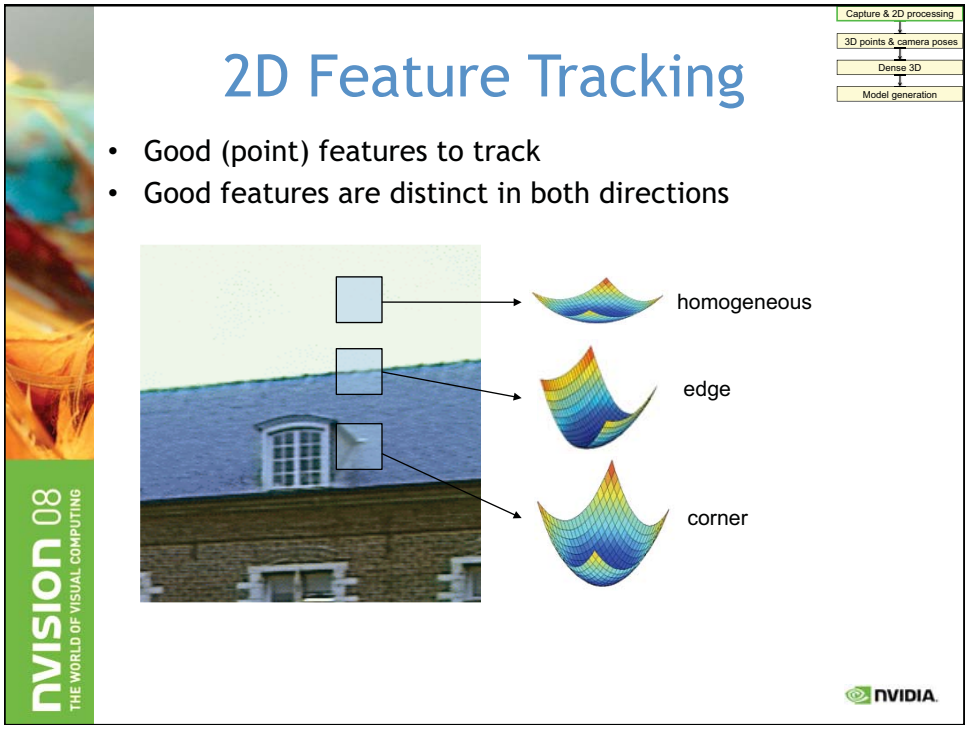
Capture & 2D processing
3D points & camera poses
Dense 3D
Model generation
2D Feature Tracking
• Good (point) features to track
• Good features are distinct in both directions
homogeneous
edge
corner
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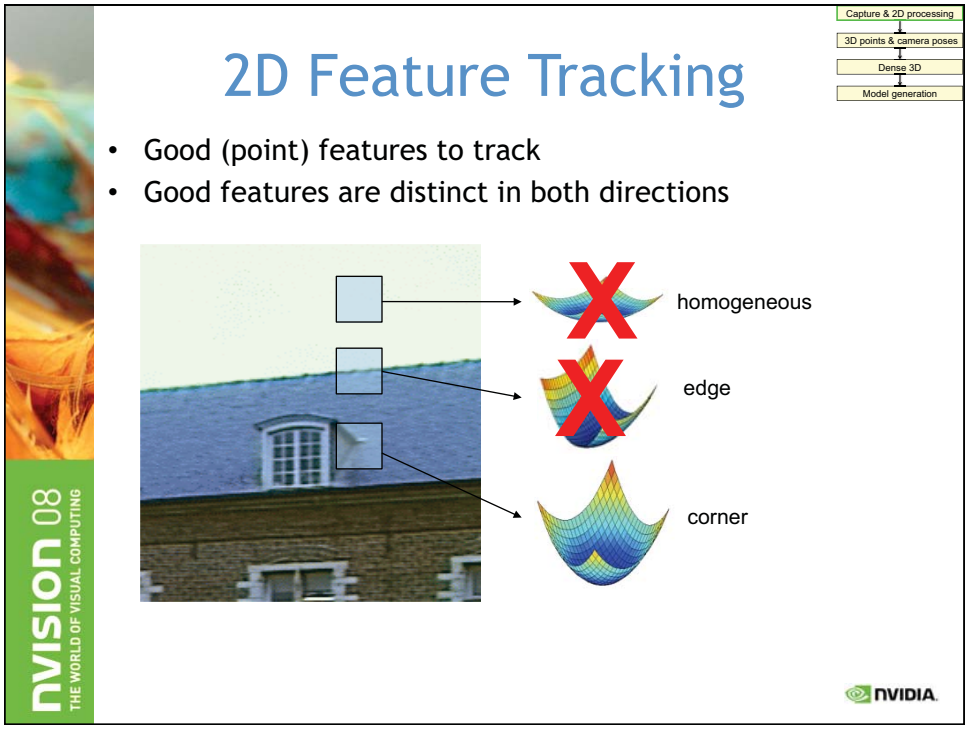
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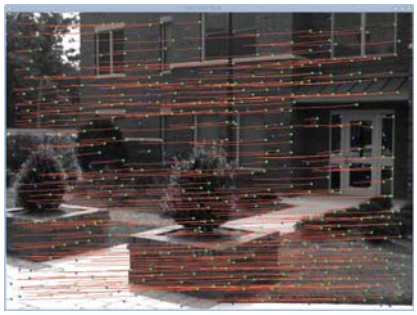
2D Feature Tracking

Capture & 2D processing
3D points & camera poses
Dense 3D
Model generation

- Establish correspondences between identical points in images
- Assumption: image content varies slowly/smoothly
  - Video sequences

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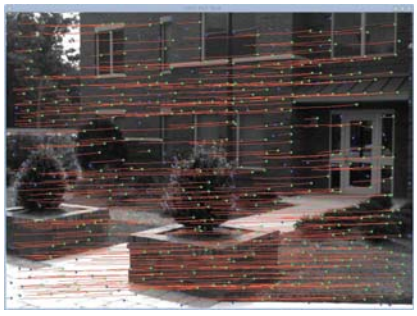

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Capture & 2D processing
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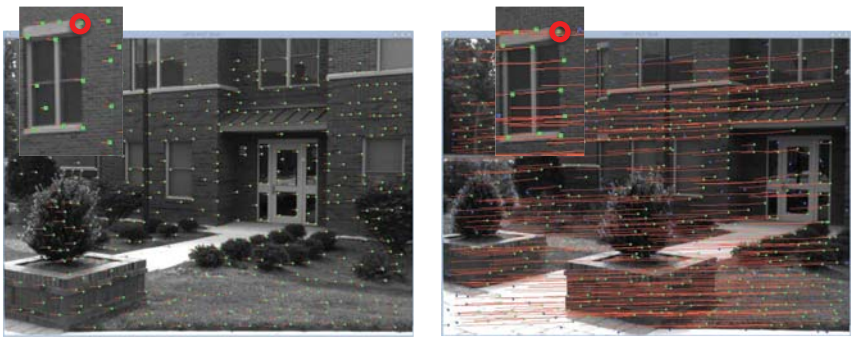

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Gain-Adaptive KLT-Tracking

Capture & 2D processing
3D points & camera poses
Dense 3D
Model generation

Kim et al. ICCV 2007

Video with fixed gain

- Simultaneous tracking and radiometric calibration
  - But: not data parallel – hard for GPU acceleration
- Continuous energy optimization [Zach et al. CVGPU'08]
  + Data parallel, very efficient on GPU

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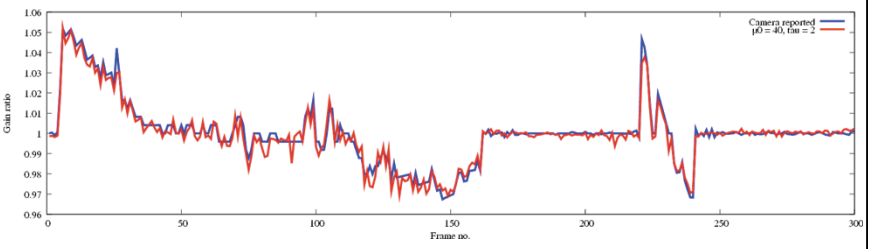
Gain Estimation

Capture & 2D processing
3D points & camera poses
Dense 3D
Model generation

- Camera reported (blue) and estimated gains (red)



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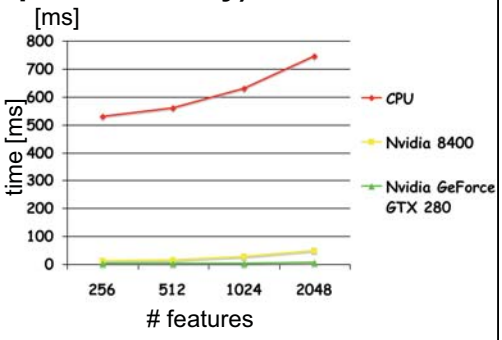
GPU-KLT

Sinha, Frahm, Pollefeys and Genc, Machine, Vision and Applications 07
Zach, Gallup, Frahm CVGPU'08

Capture & 2D processing
3D points & camera poses
Dense 3D
Model generation

On CPU with 1000 features in 1024x768 video in 630 ms (Daimler only needs ~100ms on their bold machine without gain and no sub-pixel accuracy)



On GeForce GTX 280 3.3 ms! Speedup of ~190x (still ~ 30 compared to Daimlers CPU)

Code available at: www.cs.unc.edu/~cmzach/klt

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3D model from video

Capture & 2D processing

images, 2D feature correspondences

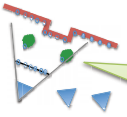
3D points & camera poses

images, camera poses

Dense 3D

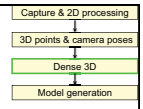
images, camera poses, depth maps

Model generation



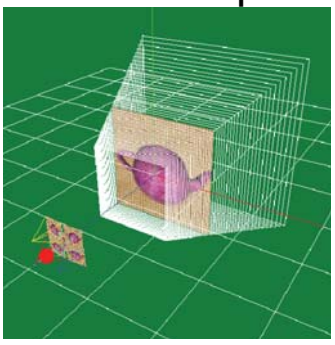
Research Roundtable: Computer Vision and Image Processing (1pm, SJCC J4)

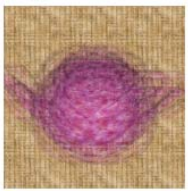
Fast GPU-based plane-sweeping stereo

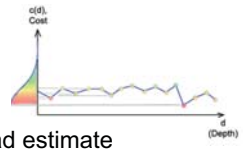


(Yang & Pollefeys, CVPR'03)

- Plane-sweep multi-view depth



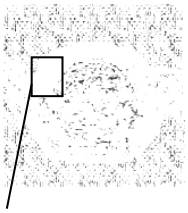




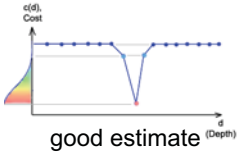
bad estimate

Confidence:

$$\left(\sum_{d \neq d_0} e^{-(\sigma(d) - \sigma(d_0))^2 / \sigma^2} \right)^{-1}$$



- For each plane similarity SSD = $(I_1-I_2)^2$
- Chose maximum similarity as best match



good estimate

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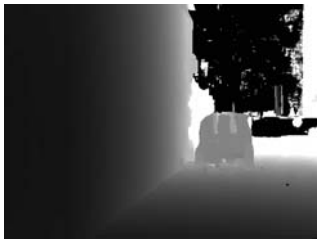
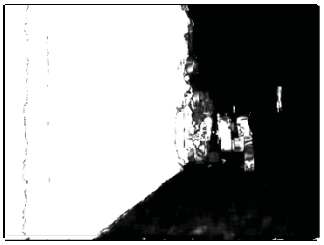
Confidence Results

Capture & 2D processing
3D points & camera poses
Dense 3D
Model generation

Captured Image



Stereo Depth Map



Confidence Map

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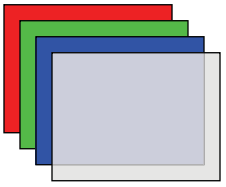
Compute SSAD per plane

Capture & 2D processing
3D points & camera poses
Dense 3D
Model generation

- 4 planes at a time, 1 plane per color channel



plane 0
plane 1
plane 2
plane 3

- Compute plane homographies
  - Warps matching view into reference view, as if it were on a given plane.
  - Uses projective texture mapping

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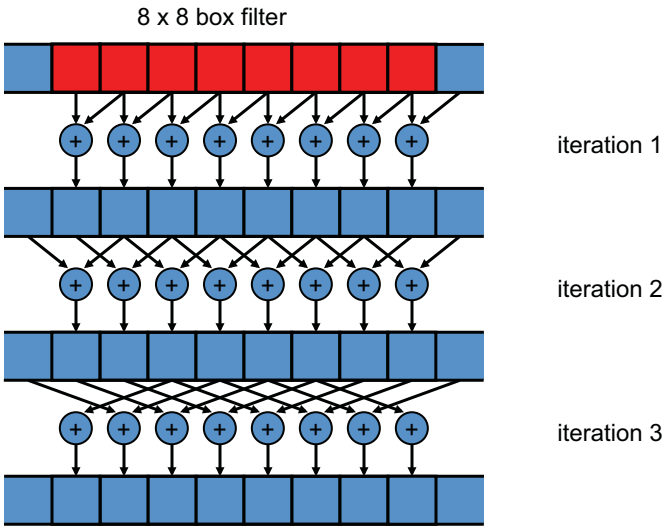
Compute SSAD per plane

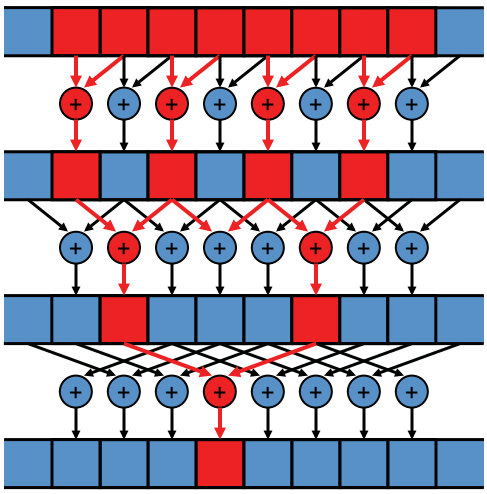
- SAD fragment shader:
  - N is compile-time constant

```
float4 sad = float4(0,0,0,0);
for(i=0; i<N; i++) {                              // N matching views
    float4 color;
    color[0] = tex2Dproj(tex[i],coord[i][0]);  // plane 0
    color[1] = tex2Dproj(tex[i],coord[i][1]);  // plane 1
    color[2] = tex2Dproj(tex[i],coord[i][2]);  // plane 2
    color[3] = tex2Dproj(tex[i],coord[i][3]);  // plane 3
    sad += abs(refColor-color);
}
```


Aggregate with box filter



Aggregate with box filter



iteration 1

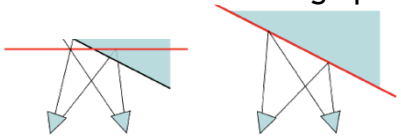
iteration 2

iteration 3

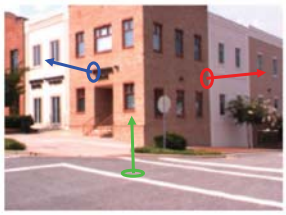
Multi-directional planes

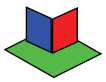
Gallup, Frahm, Mordohai, Pollefeys CVPR 07

- Improved stereo through plane alignment



- Urban scenes typically have three dominant surface normals

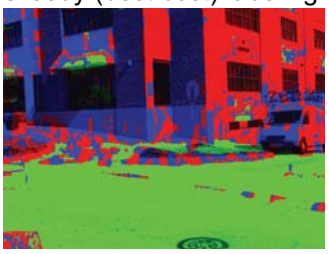




- Planes can be automatically estimated from planar camera motion assumption and vanishing points

Depth Results from Stereo

Greedy (best cost) labeling



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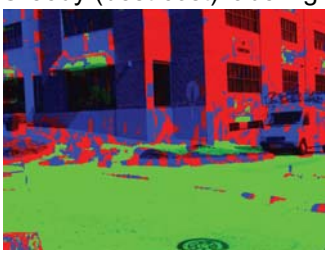
GPU-Based Global Labeling

Goal: assign a label to each pixel, such that

- The overall data (label) cost is small, and
- Neighboring pixels prefer the same label
  - Spatial regularization or smoothness
- Graph cut optimization 2s
- Continuous energy with Potts model 60 ms

Speedup ~33 on Nvidia GeForce 8800 GTX

Greedy (best cost) labeling



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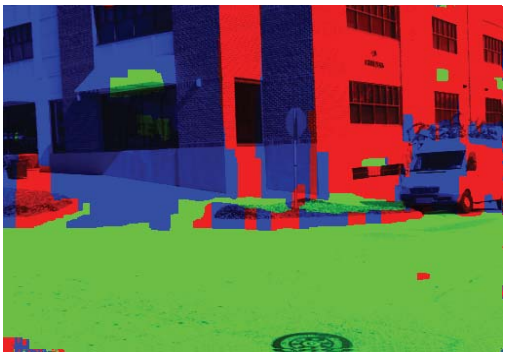
Multi-way plane-sweep Stereo

Gallup, Frahm, Mordohai, Pollefeys CVPR 07

Capture & 2D processing
3D points & camera poses
Dense 3D
Model generation



Color labels correspond to selected sweeping direction

After label optimization

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Stereo results

Capture & 2D processing
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Video side camera

Depth side camera

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3D model from video

Capture & 2D processing

images, 2D feature correspondences

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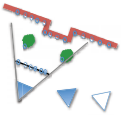
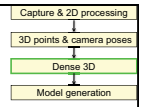
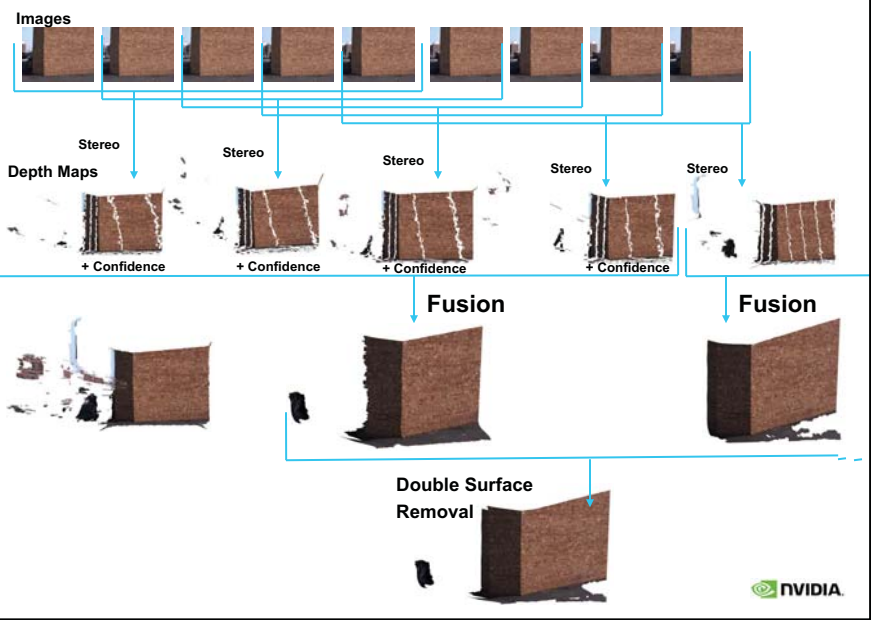


Consensus Surface Fusion on GPU

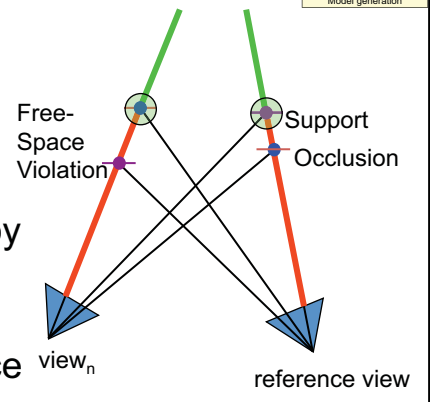
Merrel et al. ICCV'07



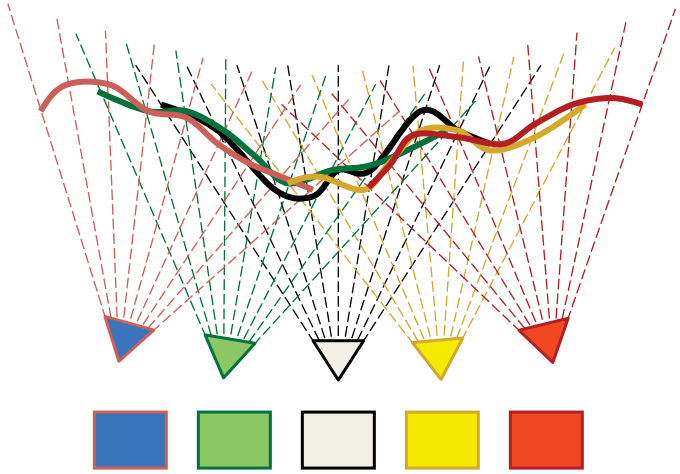


Visibility Relationships

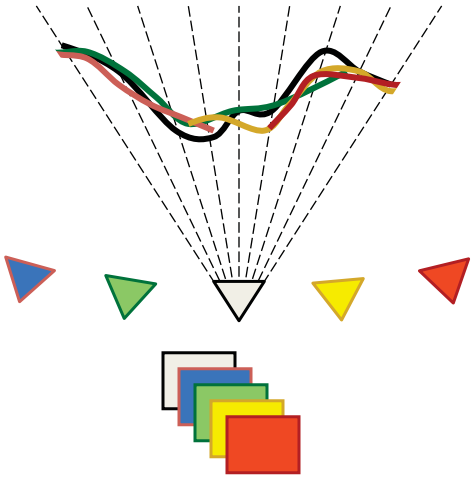
- Render all depth maps into reference view
- Choose most confident points along rays
- Add support from nearby points
- Remove support for occlusions and free-space violations
- Reject points with too little support



Render depthmaps to reference

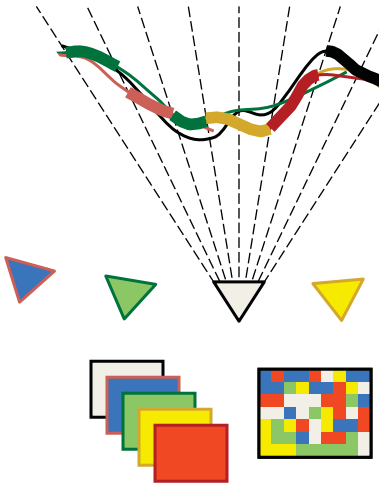


Render depthmaps to reference



- Point rendering
- Z buffer

Choose most Confident

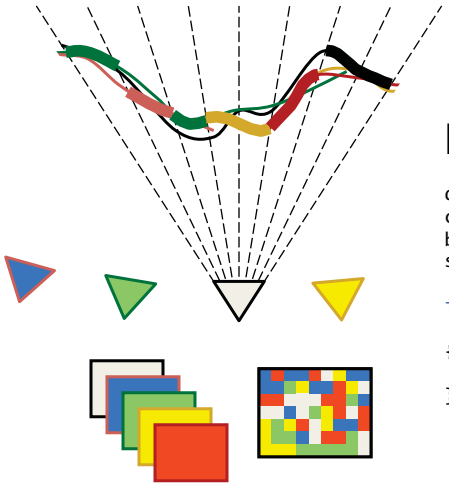


For each depthmap:

```
depth     = tex2D(tex,coord).x;
conf      = tex2D(tex,coord).y;
bestDepth = tex2D(texBest,coord).x;
bestConf  = tex2D(texBest,coord).y;

if(conf > bestConf)
{
    bestDepth = depth;
    bestConf  = conf;
}
OUT.color =
    float2(bestDepth,bestConf);
```

Add support from nearby points



Capture & 2D processing
3D points & camera poses
Dense 3D
Model generation

For each depthmap:

```
depth     = tex2D(tex,coord).x;
conf      = tex2D(tex,coord).y;
bestDepth = tex2D(texBest,coord).x;
support   = tex2D(texBest,coord).z;

if(depth < bestDepth*1.05
   && depth > bestDepth*0.95)
{
    support += conf;
}
```

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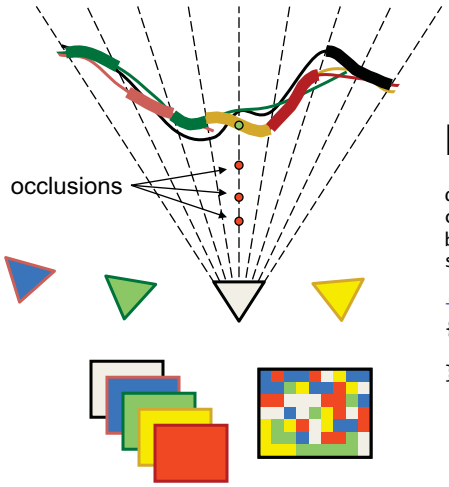
Remove support for occlusions



Capture & 2D processing
3D points & camera poses
Dense 3D
Model generation

For each depthmap:

```
depth     = tex2D(tex,coord).x;
conf      = tex2D(tex,coord).y;
bestDepth = tex2D(texBest,coord).x;
support   = tex2D(texBest,coord).z;

if(depth < bestDepth*0.95)
{
    support -= conf;
}
```

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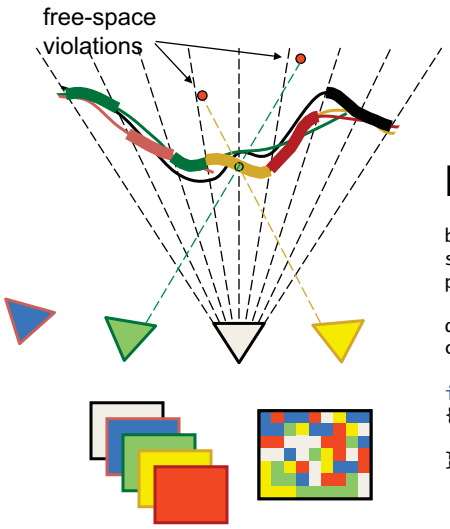
Remove support for free-space violations

Capture & 2D processing
3D points & camera poses
Dense 3D
Model generation



For each depthmap:

```
bestDepth = tex2D(texBest,coord).x;
support   = tex2D(texBest,coord).z;
pt = mul(P,float4(coord.x,coord.y
                  bestDepth,1));
depth = tex2Dproj(tex,pt).x;
conf  = tex2Dproj(tex,pt).y;

if(depth > pt.z*1.05)
{
    support -= conf;
}
```

points with too little support are then rejected

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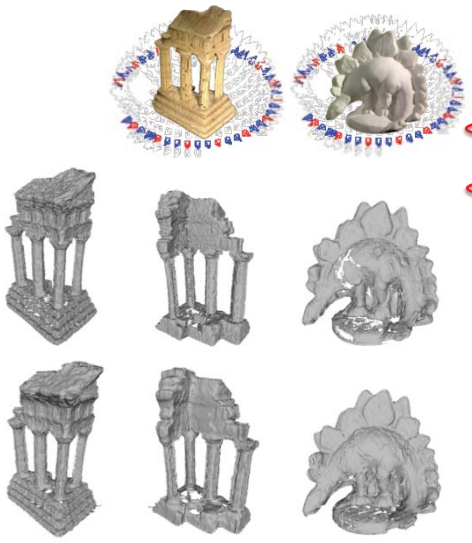
Middlebury 3D Evaluation

Merrell et al., ICCV 07 & VRML 07

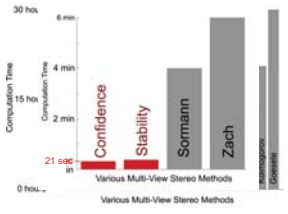
Capture & 2D processing
3D points & camera poses
Dense 3D
Model generation



Ring datasets: 47 images

	Accuracy	Completeness	Time
TEMPLE			
Stability	0.85 mm	87.0%	22 sec
Confidence	0.76 mm	85.2%	21 sec
DINO			
Stability	0.73 mm	73.1%	28 sec
Confidence	0.84 mm	83.1%	21 sec

Results competitive but much, much faster (30 hours → 30 seconds)



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Example Curb Reconstruction

Capture & 2D processing
3D points & camera poses
Dense 3D
Model generation

Courtesy Daimler

Example Curb Reconstruction

Capture & 2D processing
3D points & camera poses
Dense 3D
Model generation

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3D model from video

Capture & 2D processing
3D points & camera poses
Dense 3D
Model generation

Capture & 2D processing

images, 2D feature correspondences

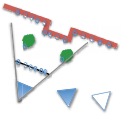
3D points & camera poses

images, camera poses

Dense 3D

images, camera poses, depth maps

Model generation



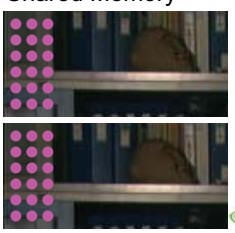
CUDA Stereo

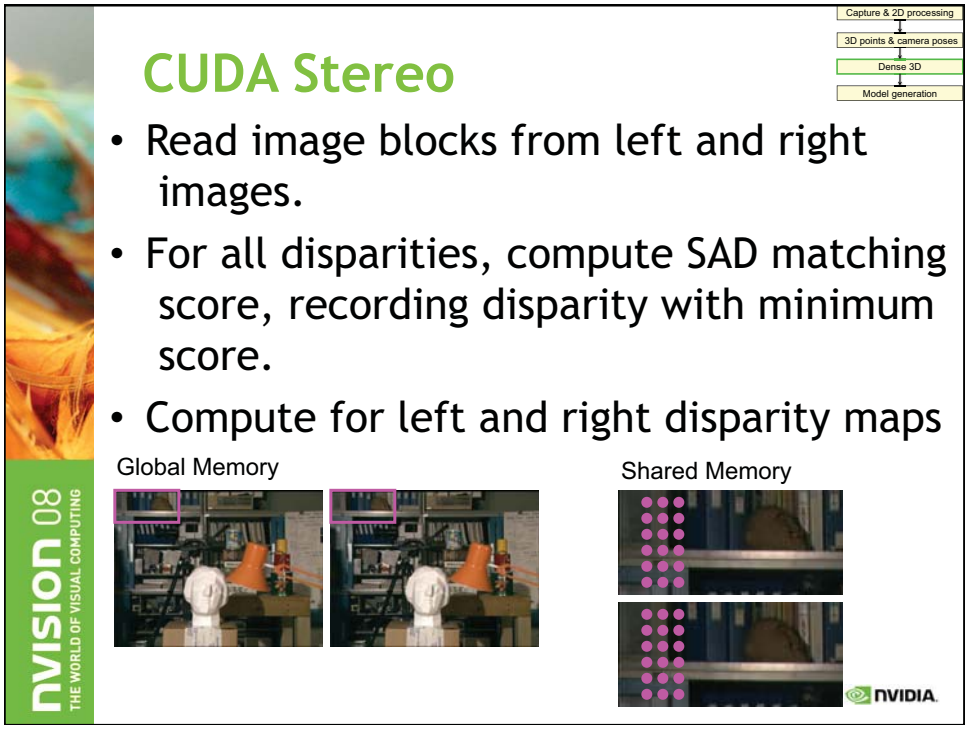
Capture & 2D processing
3D points & camera poses
Dense 3D
Model generation

- Read image blocks from left and right images.
- For all disparities, compute SAD matching score, recording disparity with minimum score.
- Compute for left and right disparity maps

Global Memory

Shared Memory




Capture & 2D processing
3D points & camera poses
Dense 3D
Model generation
CUDA Stereo
• Read image blocks from left and right images.
• For all disparities, compute SAD matching score, recording disparity with minimum score.
• Compute for left and right disparity maps
Global Memory
Shared Memory
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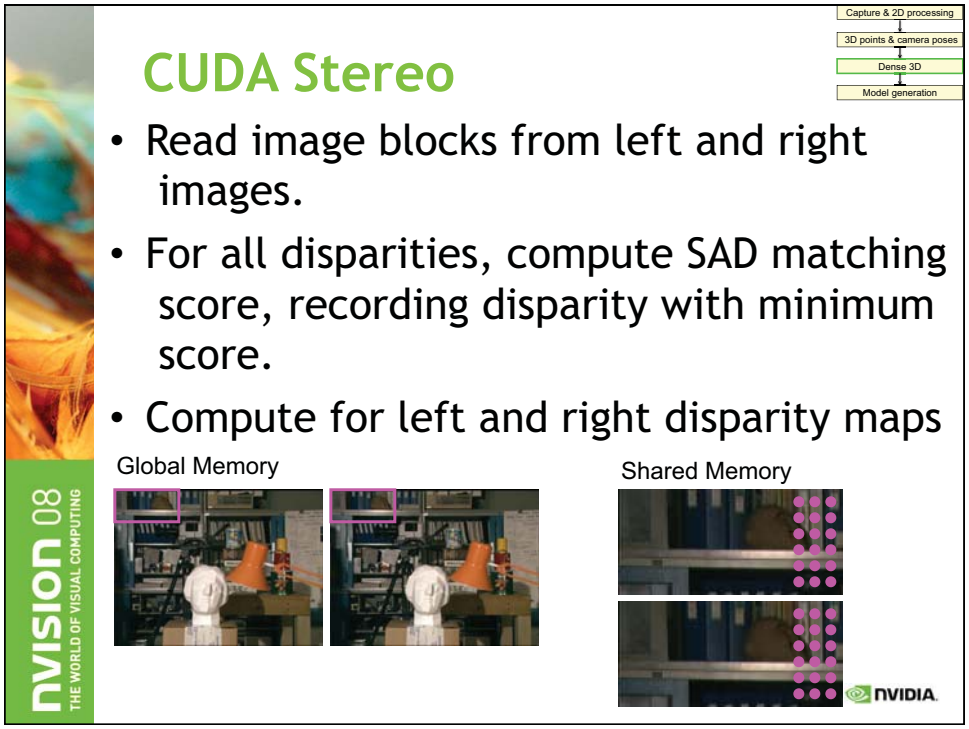
Capture & 2D processing
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Global Memory
Shared Memory
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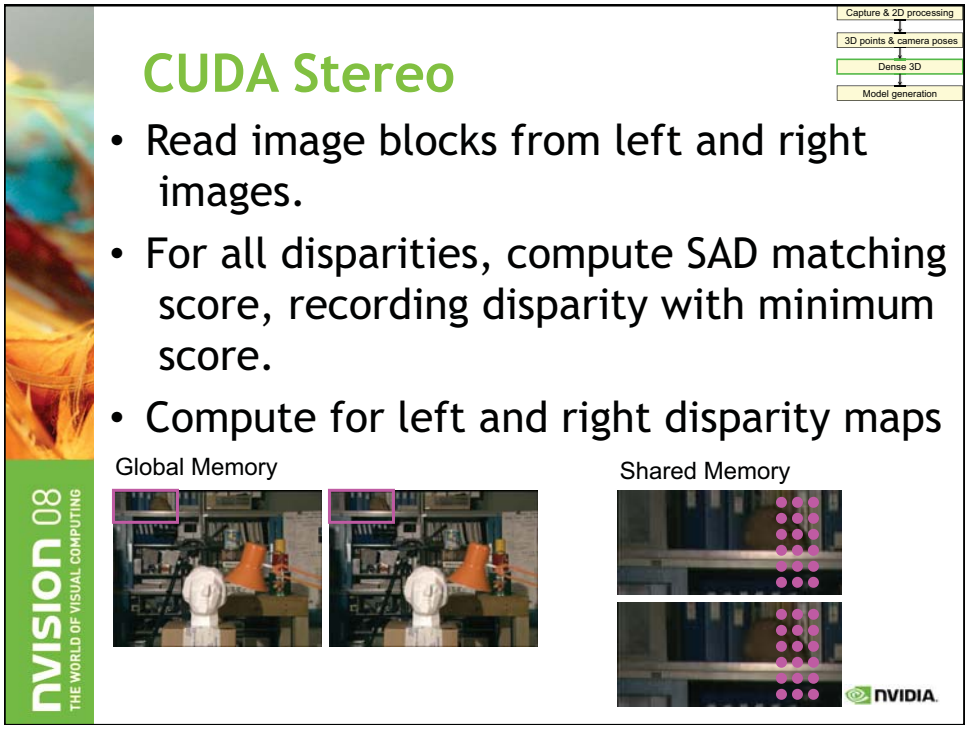
Capture & 2D processing
3D points & camera poses
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Model generation
CUDA Stereo
• Read image blocks from left and right images.
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Global Memory
Shared Memory
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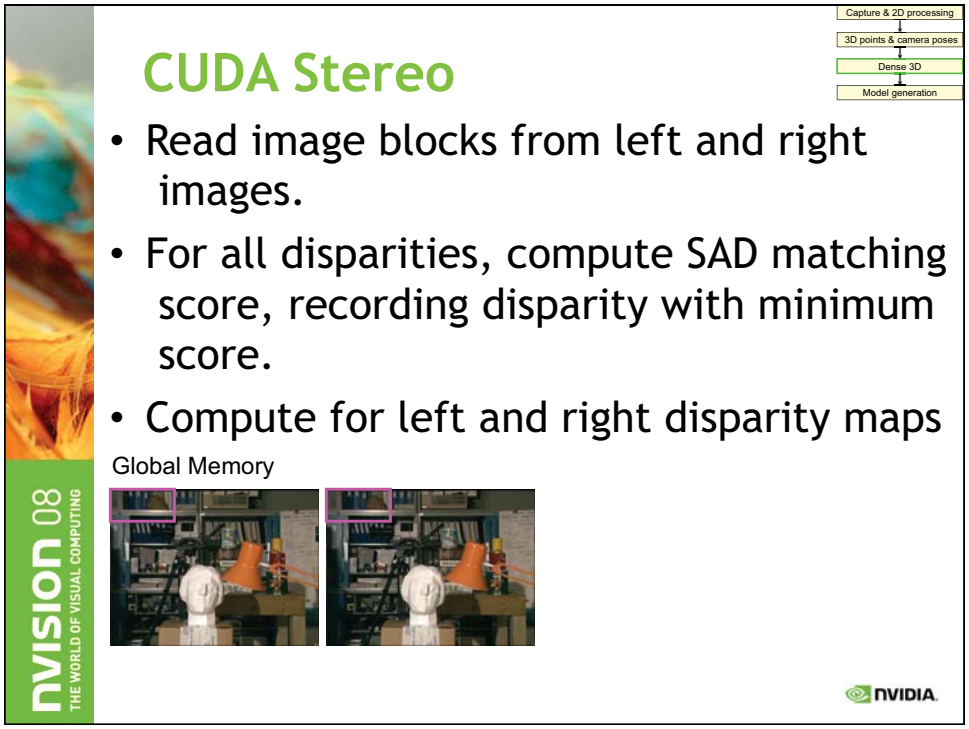
Capture & 2D processing
3D points & camera poses
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Global Memory
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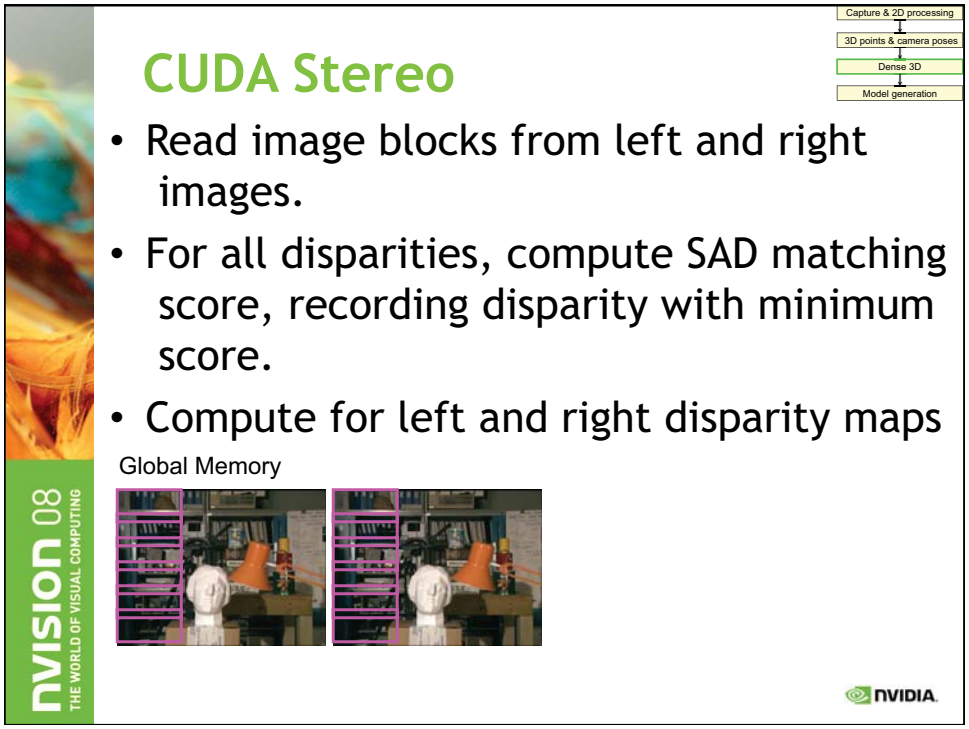
Capture & 2D processing
3D points & camera poses
Dense 3D
Model generation
CUDA Stereo
• Read image blocks from left and right images.
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Global Memory
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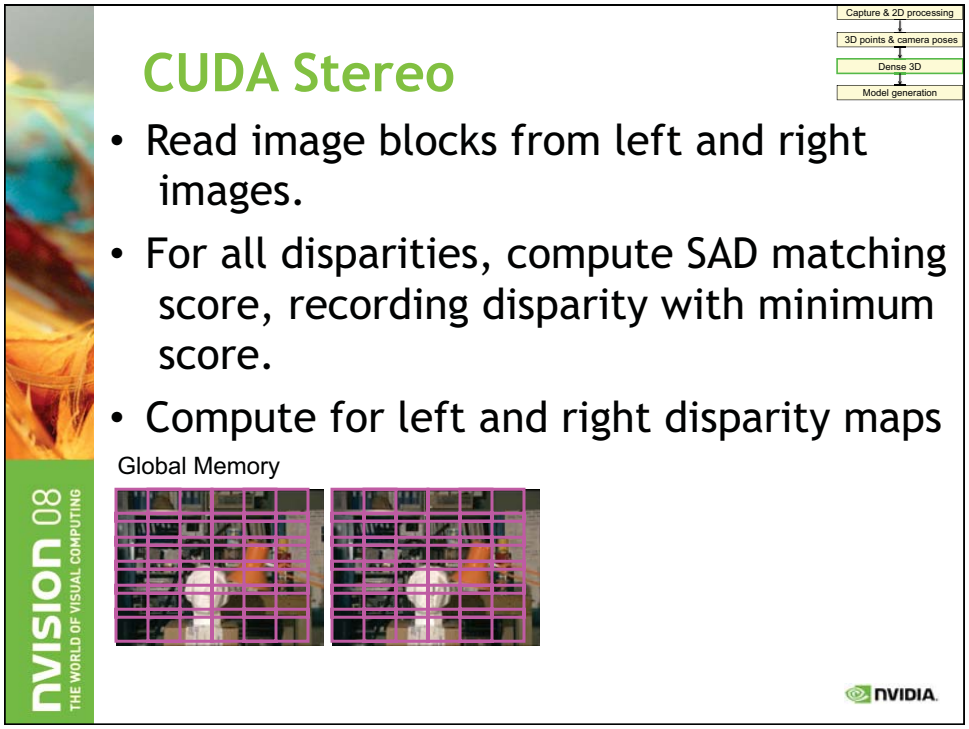
Capture & 2D processing
3D points & camera poses
Dense 3D
Model generation
CUDA Stereo
• Read image blocks from left and right images.
• For all disparities, compute SAD matching score, recording disparity with minimum score.
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Global Memory
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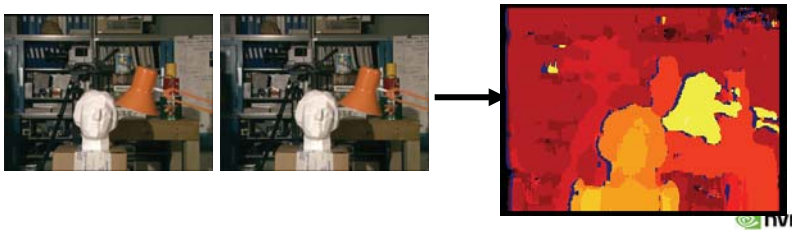
CUDA Stereo

Capture & 2D processing
3D points & camera poses
Dense 3D
Model generation

- Detect occlusions and outliers by left /right depthmap consistency check.
  - If pixel x in left image corresponds to x' in right image, then x' should correspond to x, or one of its neighbors.

$$\left|D_L(x) - D_R(x + D_L(x))\right| \le C$$

- **10% speedup compared to OpenGL**



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Two-view Stereo Results

Capture & 2D processing
3D points & camera poses
Dense 3D
Model generation

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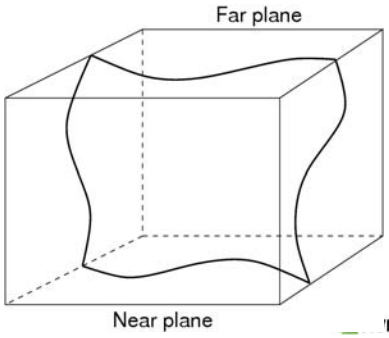
Global Stereo

Capture & 2D processing
3D points & camera poses
Dense 3D
Model generation

- Shares some similarity with global labeling
  - More labels (all possible depth values)
  - Embedded in higher dimension
- Find surface separating the near from the far plane
  - With minimal costs
    - Data cost (NCC), and
    - Smoothness cost
  - Local updates of values according to PDEs
  - Data parallel!

GPU speedup 80x
but still 4s!



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Global Stereo results

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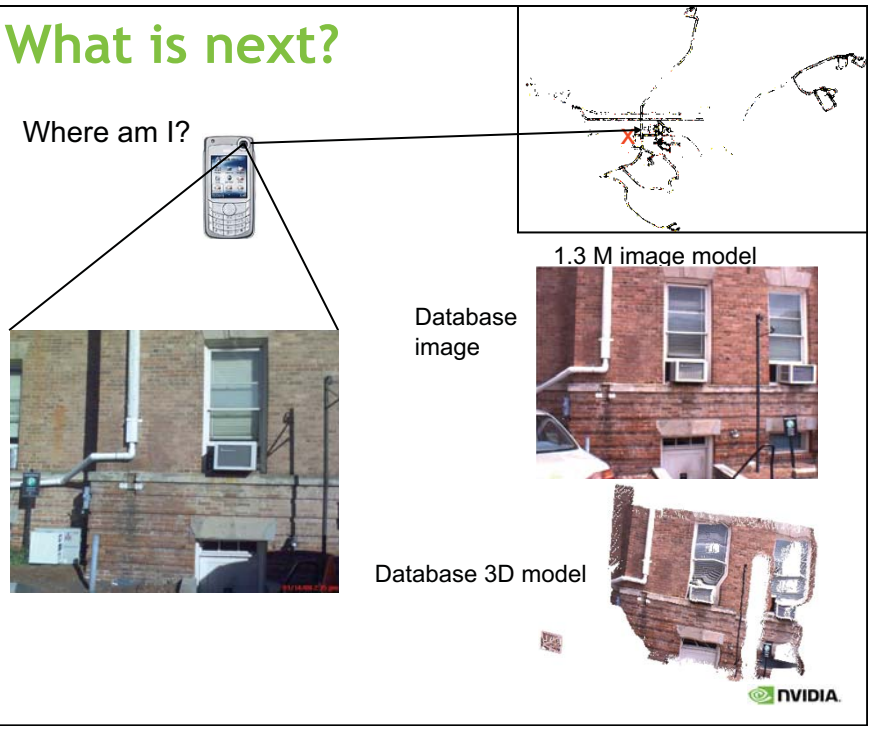
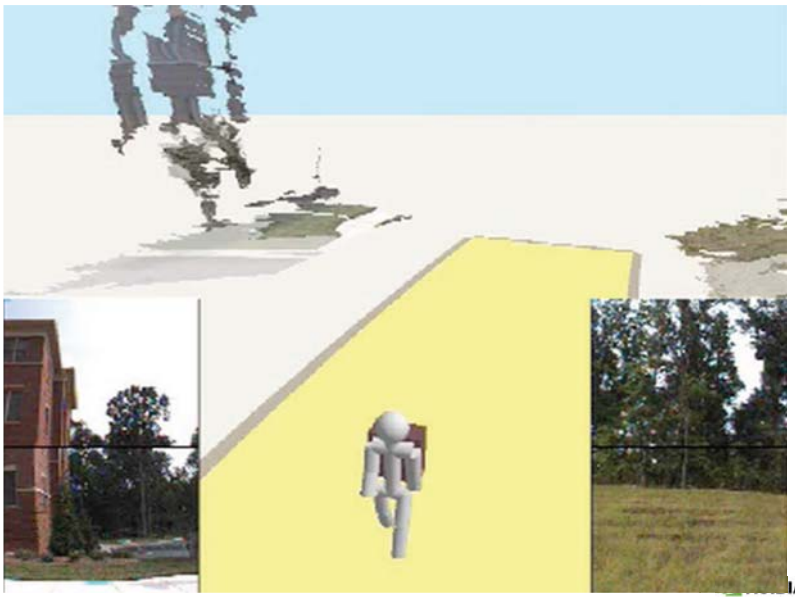
Conclusions

- GPU based real-time scene reconstruction system
  - 2D tracking on GPU
  - Stereo estimation on GPU
  - Dense map fusion on GPU
- Algorithmic redesign to better deploy the GPU

What is next?



Static Scene Reconstruction



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Thank you!

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