Structured-Light Based Acquisition (Part 2)

CS635
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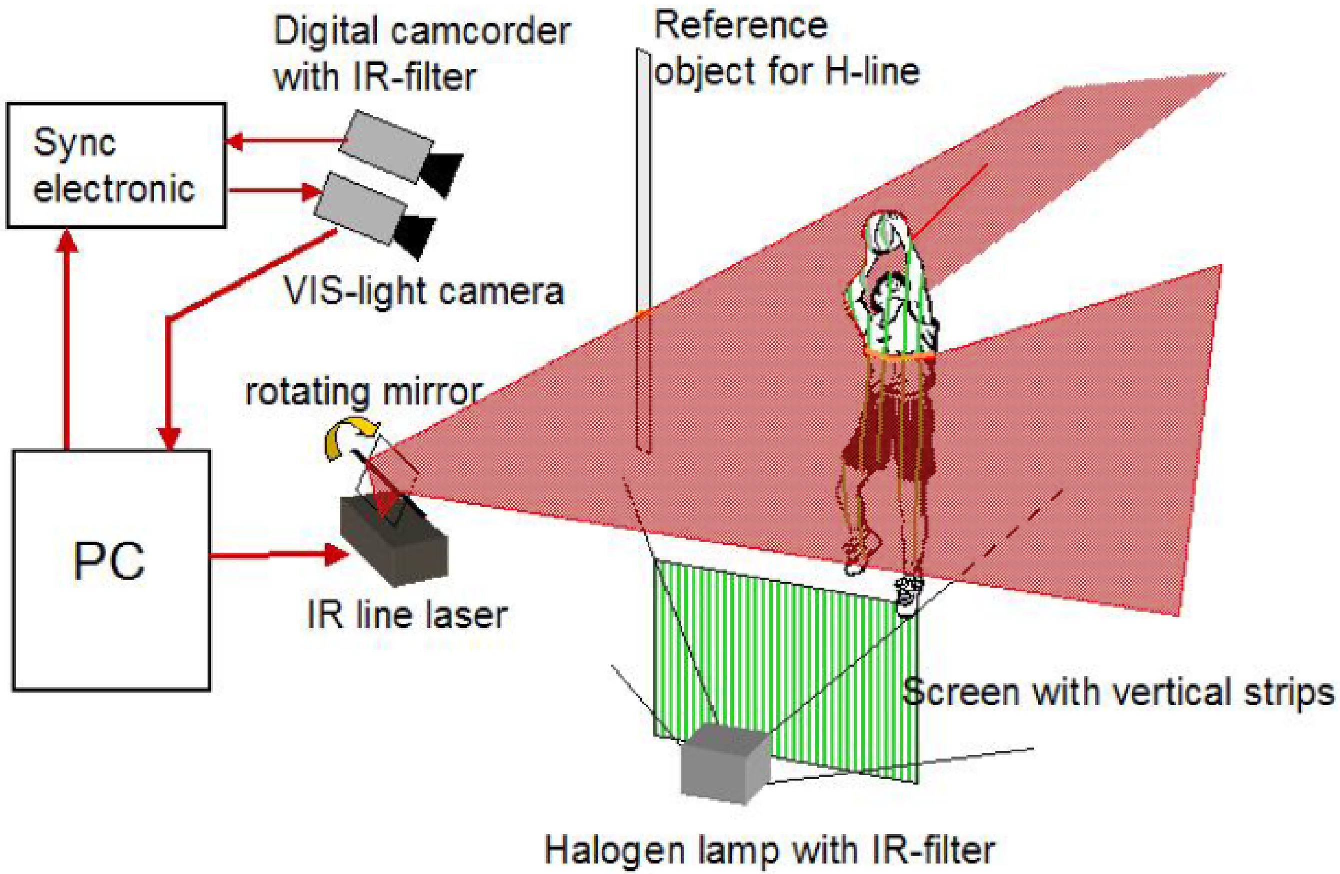
Acquiring Dynamic Scenes

- Scene: object (or camera) is moving and/or object is deforming
- Acquisition: capture as much information as possible in one to a few frames
  - By exploiting coherence
  - By exploiting several “channels” of information (e.g., color, infrared, etc…)

Capturing 2½D Depth and Texture of Time-Varying Scenes Using Structured Infrared Light



V-lines

Line defined at “middle” of IR strip

How do you know which line is which? Ideas?

H-lines

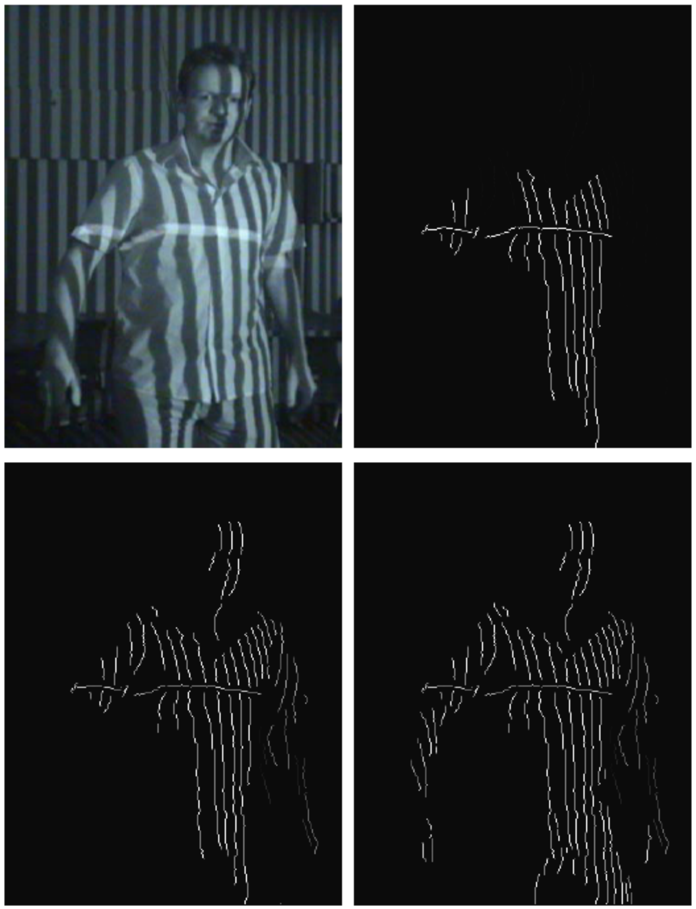
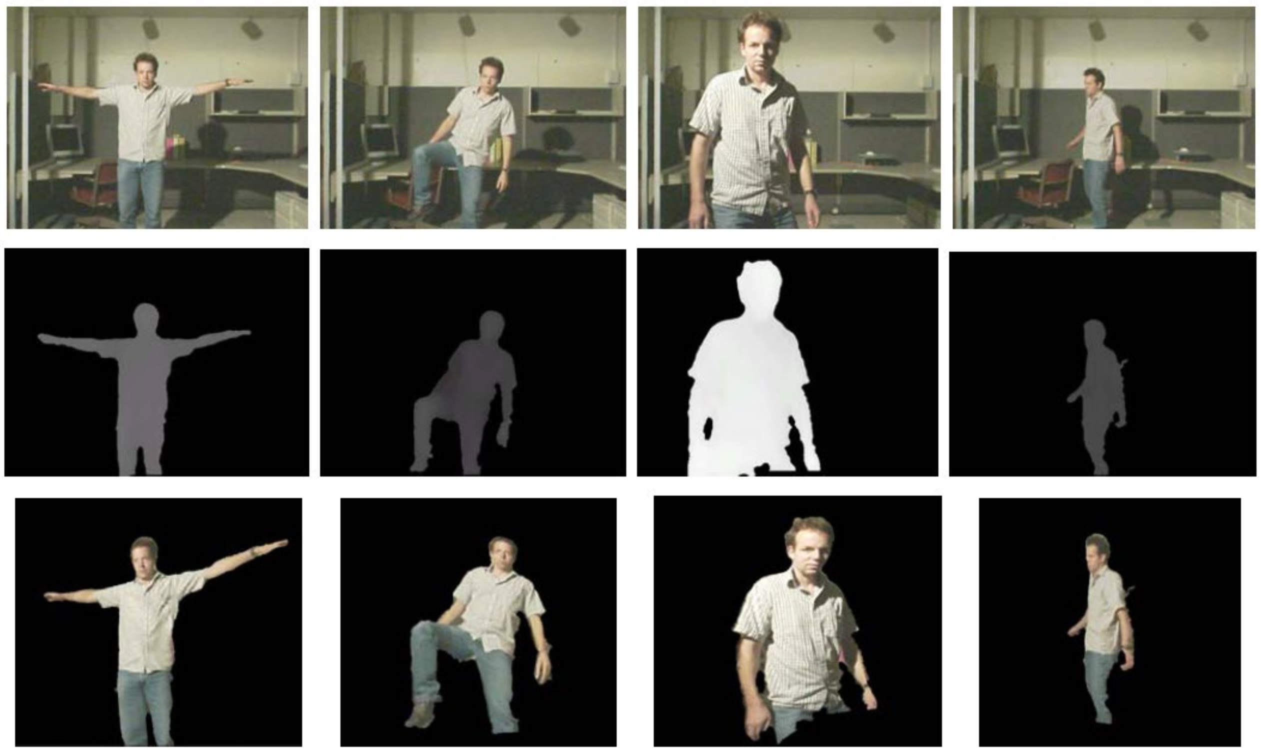


Figure 6: Reconstructing the depth along V-lines. (a) IR frame; (b) V-lines from intra-frame tracking only; (c) V-lines with additional forward inter-frame tracking, (d) final result after V-lines with both forward and backward inter-frame tracking, and line counting.

H-line sweeps up/down at 2Hz and enables an ordering of (a subset of) the V-lines and thus permits their correspondence

Additional Steps



Grab color image

Foreground segmentation, and dense depth interpolation

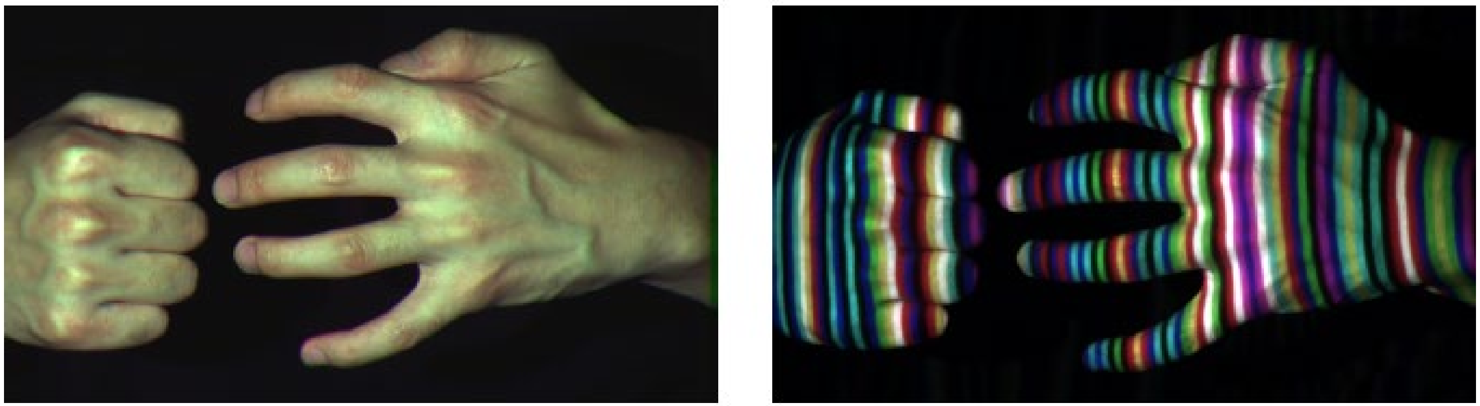
Put it all together…

IR camera at 30Hz, color camera at 10Hz
(probably faster today…)

Rapid Shape Acquisition Using Color Structured Light and Multi-pass Dynamic Programming

- Use color transitions to define features
- Define lines at the transitions from color A to color B

Rapid Shape Acquisition Using Color Structured Light and Multi-pass Dynamic Programming



- What is a notable problem?
- Resolution. Why?

Rapid Shape Acquisition Using Color Structured Light and Multi-pass Dynamic Programming

- Only have three color channels (R,G,B) and can only robustly differentiate “strong” color changes
- This reduces the number of colors to use, and
- Often results in ambiguity in the color coding

Rapid Shape Acquisition Using Color Structured Light and Multi-pass Dynamic Programming

- Challenges
  - Given a color code, how to do “best” correspond the stripes?
  - With the above in mind, how do we design a good color code?

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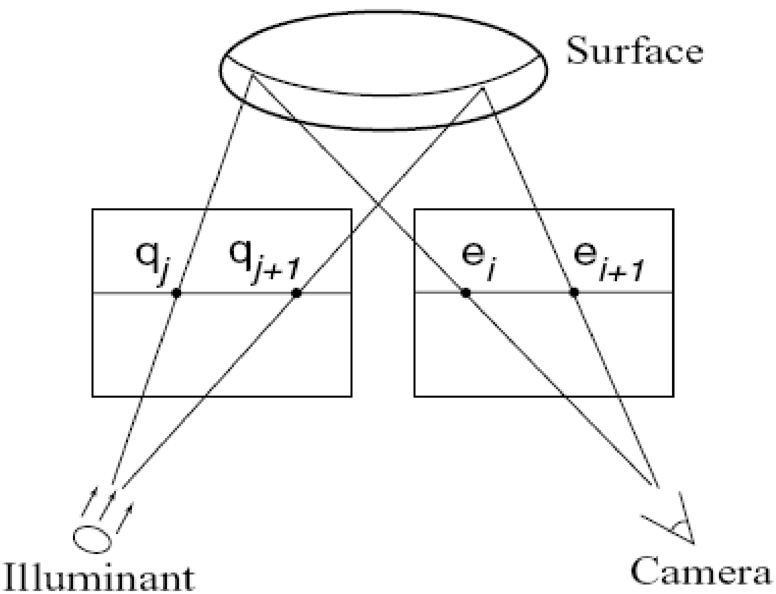
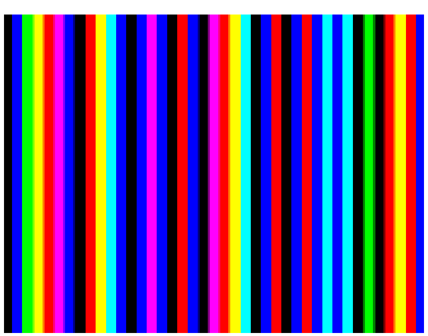
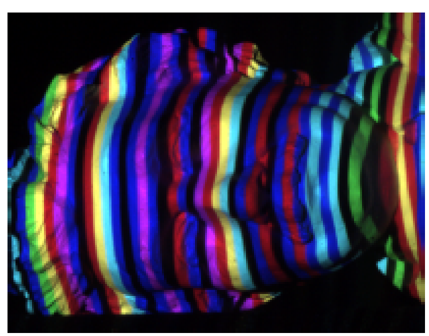
How to “best” correspond the stripes

- Solution
  - Dynamic Programming

How to “best” correspond the stripes?

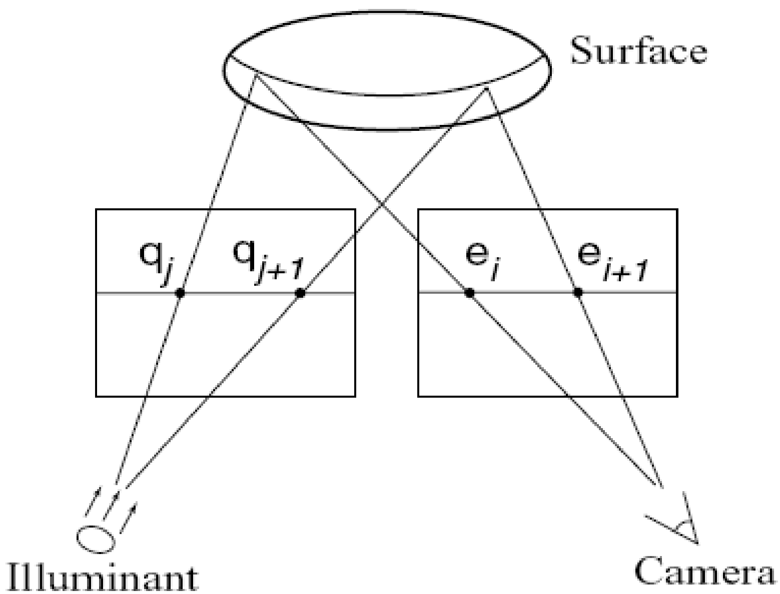


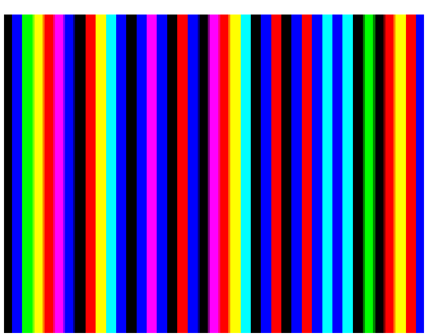


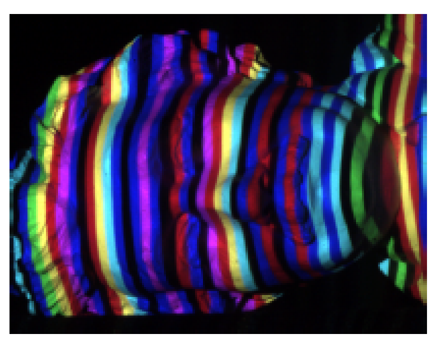


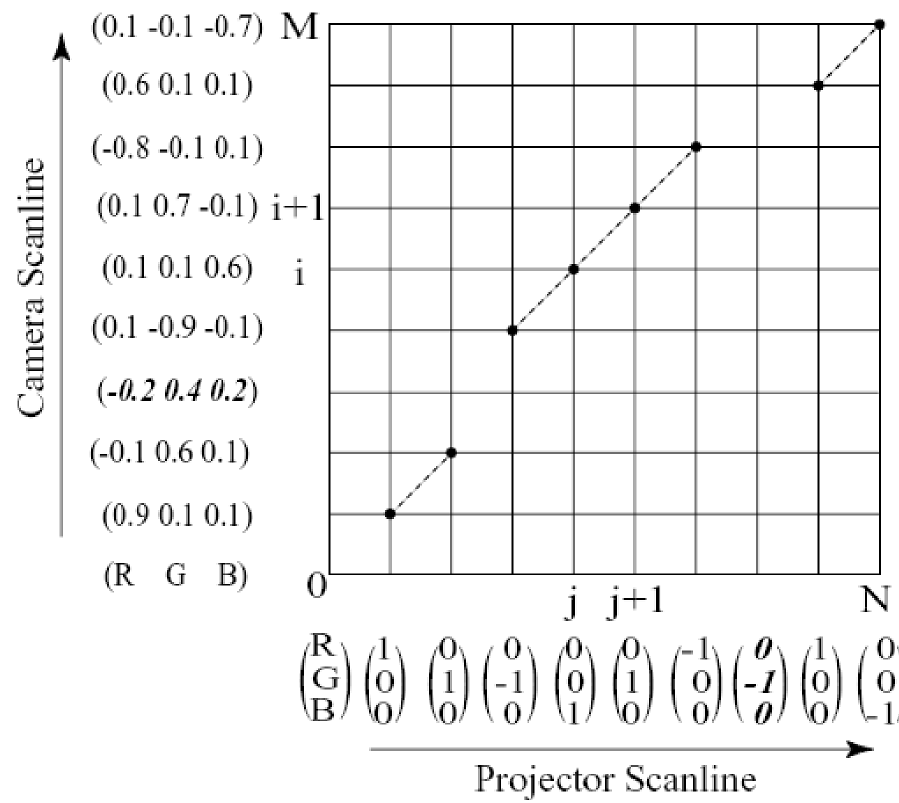
(rectified images)

How to “best” correspond the stripes?









How to "best" correspond the stripes?

Multiple match hypotheses $\phi = \left\{ \begin{pmatrix} j_1 \\ i_1 \end{pmatrix}, \begin{pmatrix} j_2 \\ i_2 \end{pmatrix}, \ldots, \begin{pmatrix} j_H \\ i_H \end{pmatrix} \right\}$

Similarity score (of color) between edge e_i and transition q_j is $s(q_j, e_i)$

Score of the entire match sequence $f(\phi) = \sum_{k=1}^{H} s(q_{j_k}, e_{i_k})$

Dynamic programming objective is: $\arg\max_{\phi}(f(\phi))$

How to “best” correspond the stripes?

Dynamic programming objective is: $\arg\max_{\phi}(f(\phi))$

However, the space all possible ϕ is very large: $O(M^N)$

Solution?

Assume monotonicity (of the depth ordering):

$$i_1 \le i_2 \le \ldots \le i_H$$

Great! But this monotonicity does **not** hold in what situation?

Occlusions! Oh well…

But it holds for individual fragments, which we can combine

How to “best” correspond the stripes?

Dynamic programming objective is: $\arg\max_{\phi}(f(\phi))$

Let optimal ϕ be called ϕ^*

$$f(\phi^*_{ji}) = \begin{cases} 0 & \text{if j=0 or i=0} \\ \max \begin{cases} f(\phi^*_{j-1,i-1}) + s(q_j, e_i) \\ f(\phi^*_{j-1,i}) \\ f(\phi^*_{j,i-1}) \end{cases} \end{cases}$$

f found through a recursive search and some optimizations to further reduce the search space (e.g., assume at most small depth changes from one column to another)

Rapid Shape Acquisition Using Color Structured Light and Multi-pass Dynamic Programming

- Challenges
  - Given a color code, how to do “best” correspond the stripes?
  - With the above in mind, how do we design a good color code?

How do we design a good color code?

- De Bruijn sequence $B(k,n)$
  - (Dutch mathematician: Nicolaas Govert de Bruijn)
  - is a <u>cyclic</u> sequence of a given alphabet A with size k for which every possible subsequence of length n in A appears as a sequence of consecutive characters exactly once
  - thus it is optimally short as well
- $B(k, n)$ has length k^n
- Example: *A={0,1}*
  - *B(2,2) = 01100*

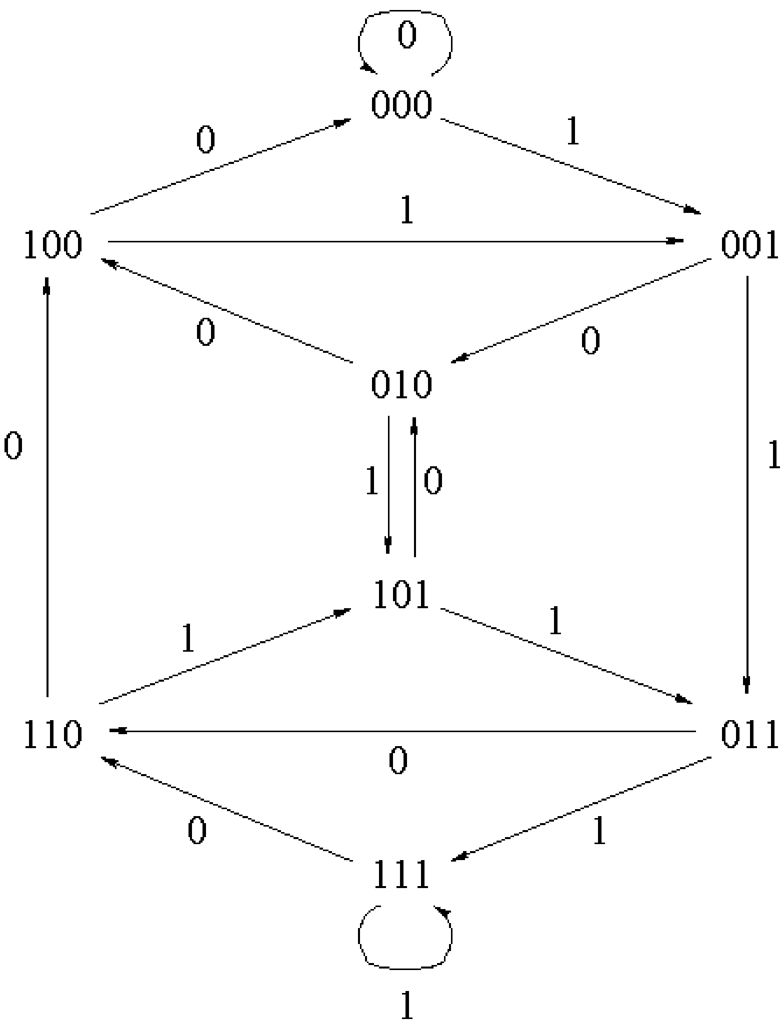
    All possible strings of length 2 (00, 01, 10, 11) appear exactly once as sub-strings in A
  - *B(2,3)= 00010111 (or 11101000)*

    All possible strings of length 3 (000, 001, 010, 011, 100, 101, 110 and 111) appear exactly once as sub-strings in A

De Bruijn sequence $B(k,n)$

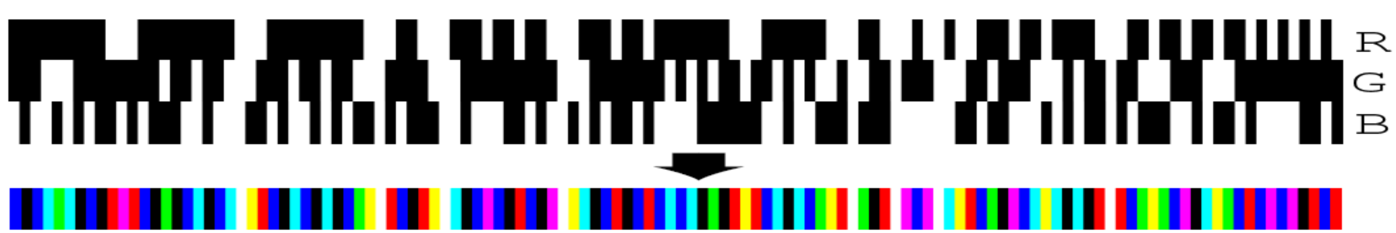
- Can also be constructed by a Hamiltonian cycle of an n-dimensional De Bruijn graph over k symbols; e.g.,

(Hamiltonian cycle means each vertex is visited once)

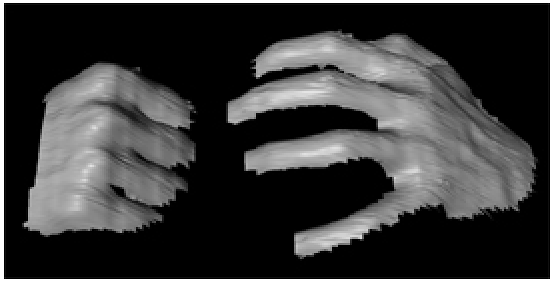


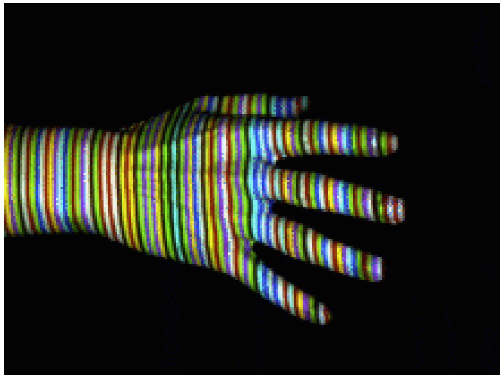
Color Sequence

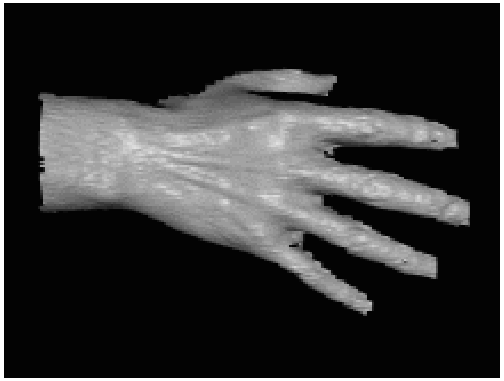
- Colors = *{000,100,110,…,111}* total of 8-1=7 because *000* is useless
- Color sequence is created by $p_{j+1}=p_j \; XOR \; d_j$
  - XOR'ing effectively "flips bits" using d_j
  - p_0 is a chosen initial color (e.g., *100*)
- Want 3 letters sequences d_j to be unique
- In practice about 125 stripes is sufficient
- Thus, a *B(5,3)* is adequate



Examples

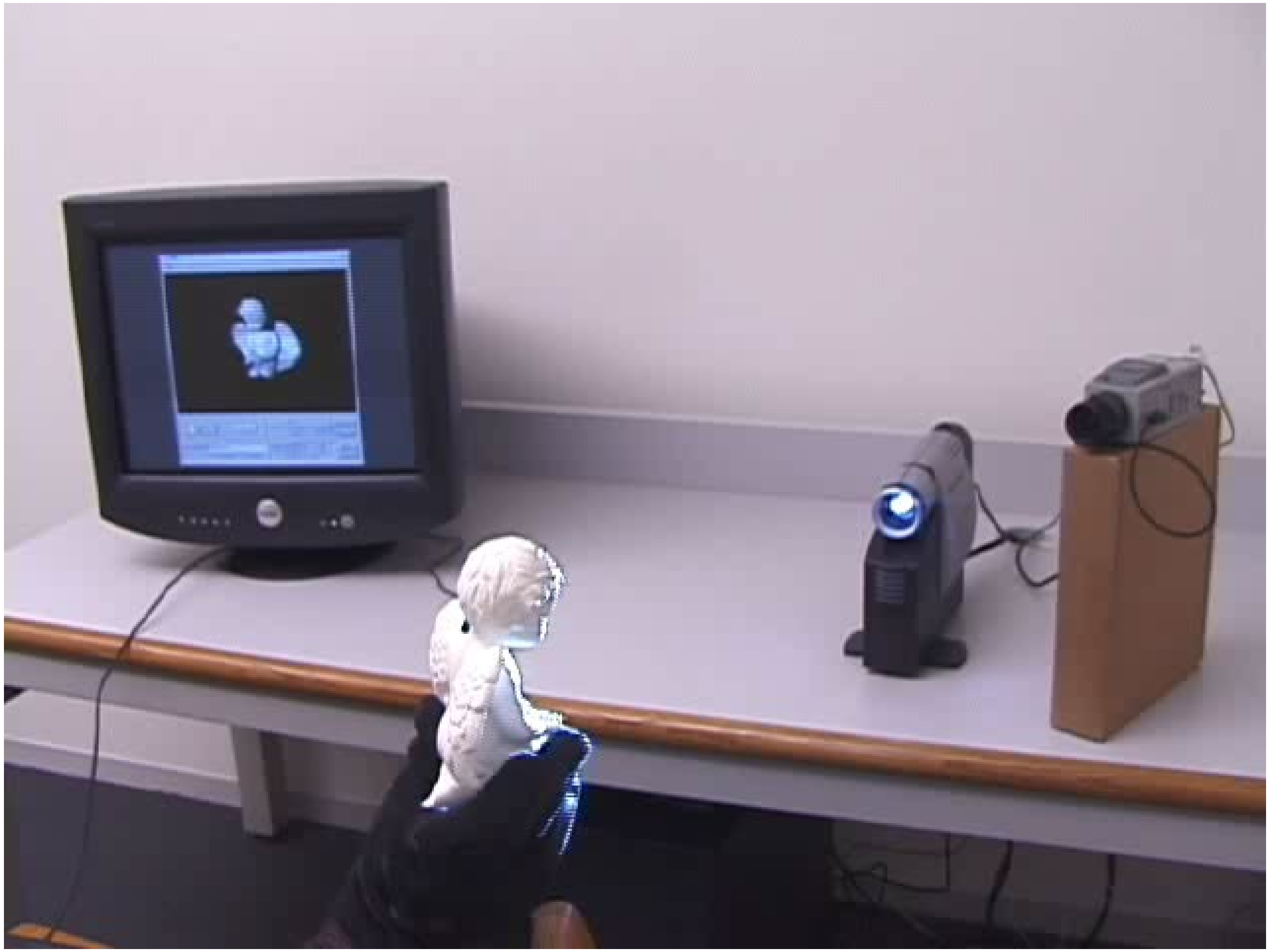




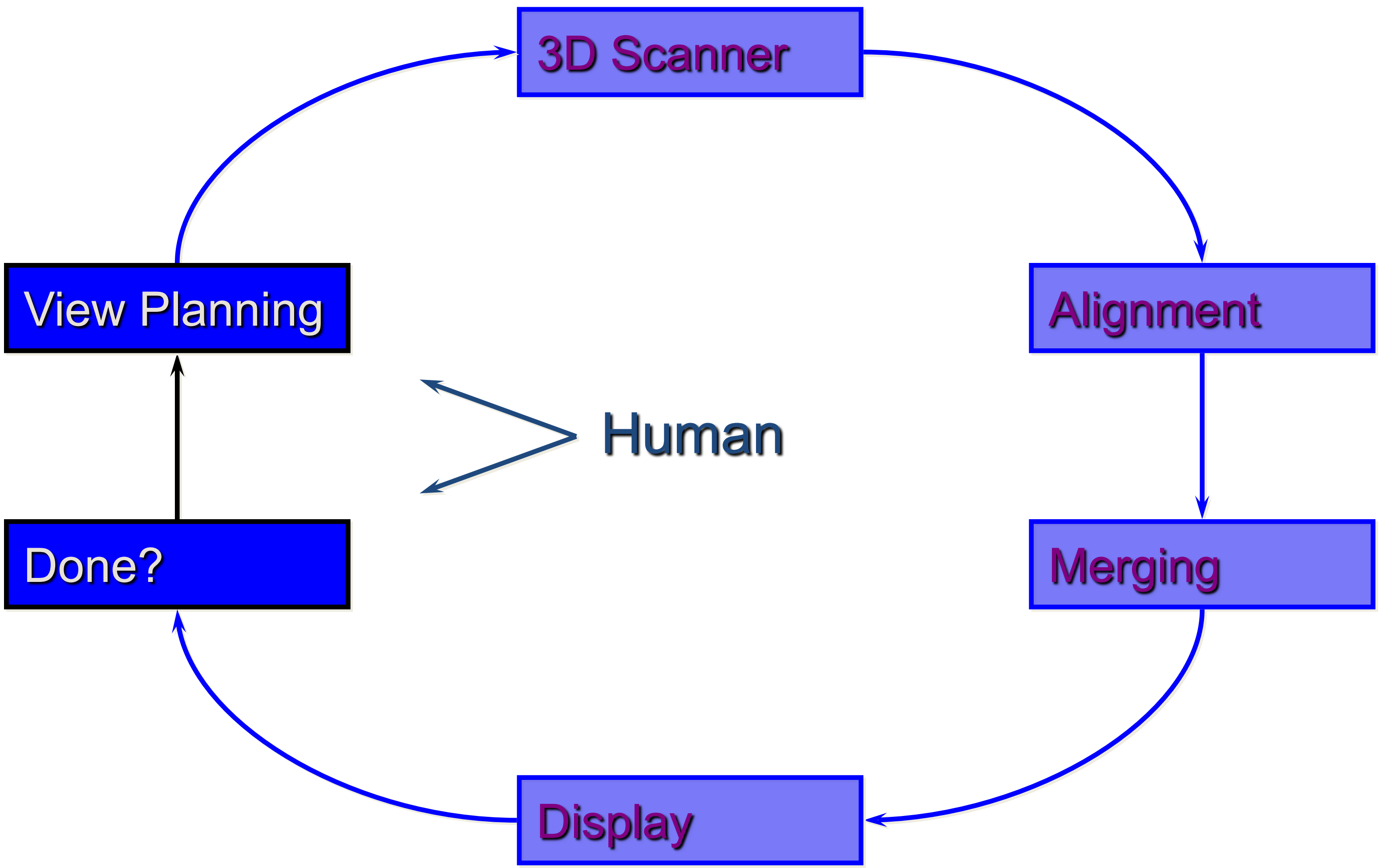


Real-Time 3D Model Acquisition

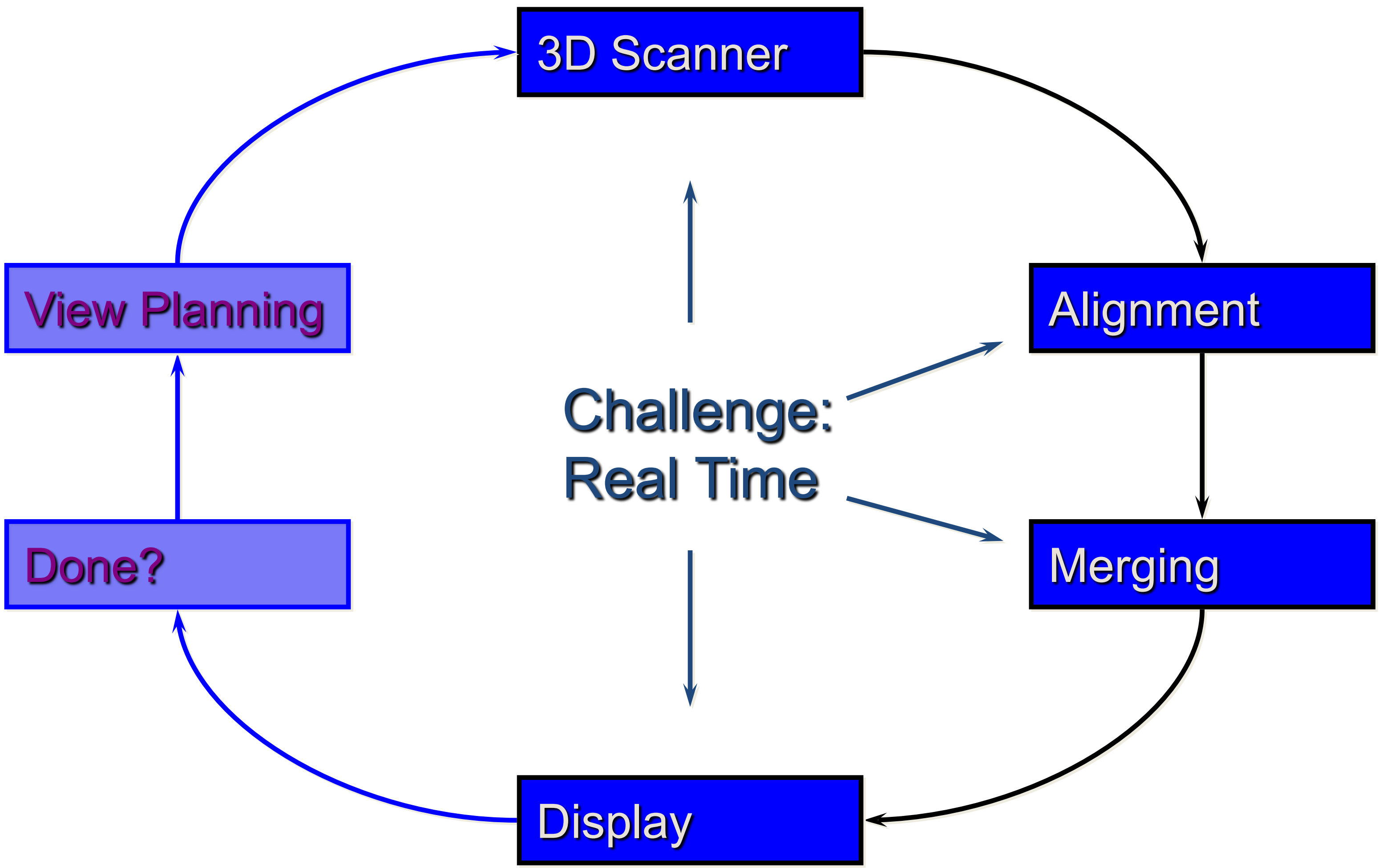
(slides and videos of this section by Syzmon Rusinkiewicz @ Princeton



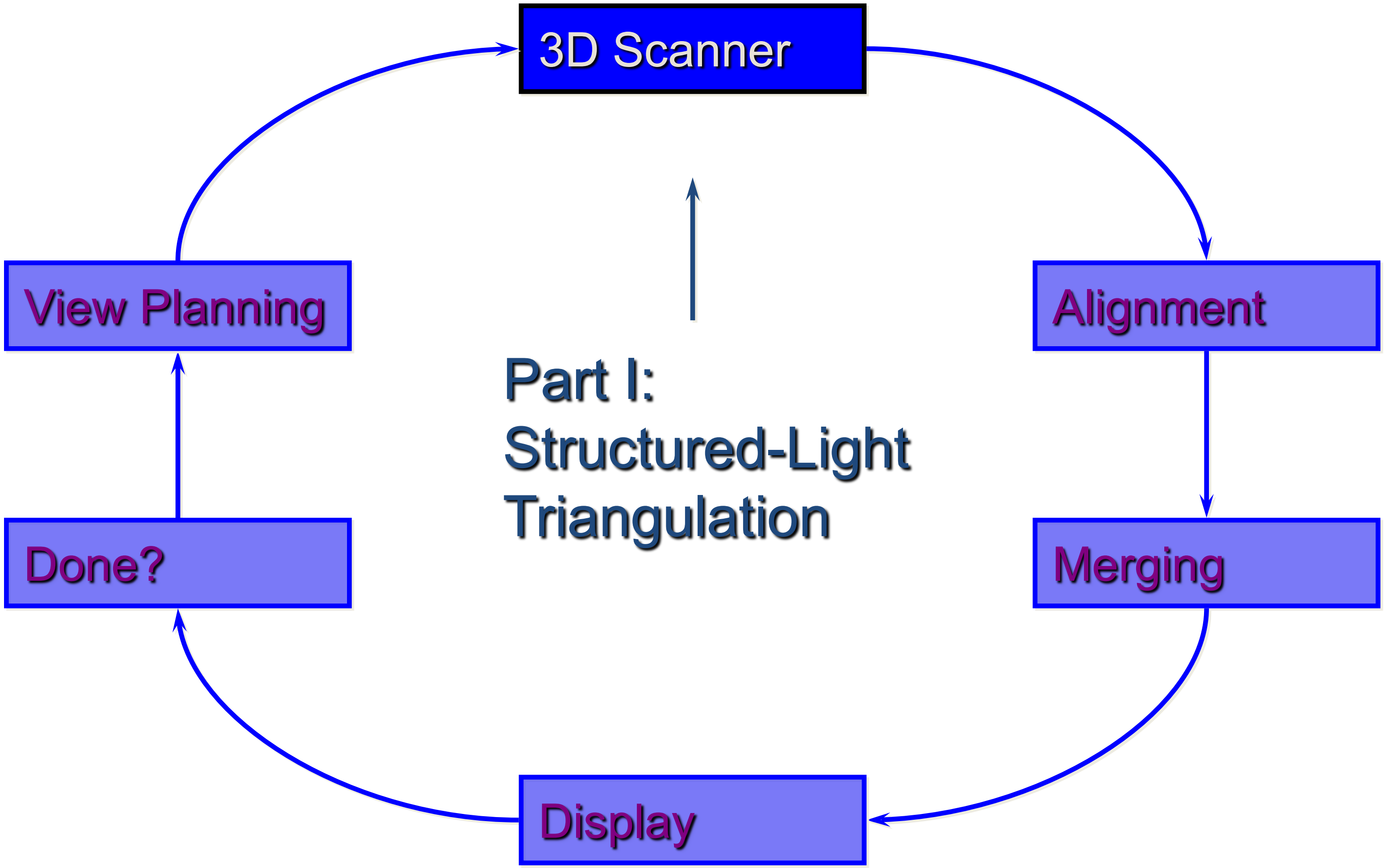
Real-Time 3D Model Acquisition Pipeline



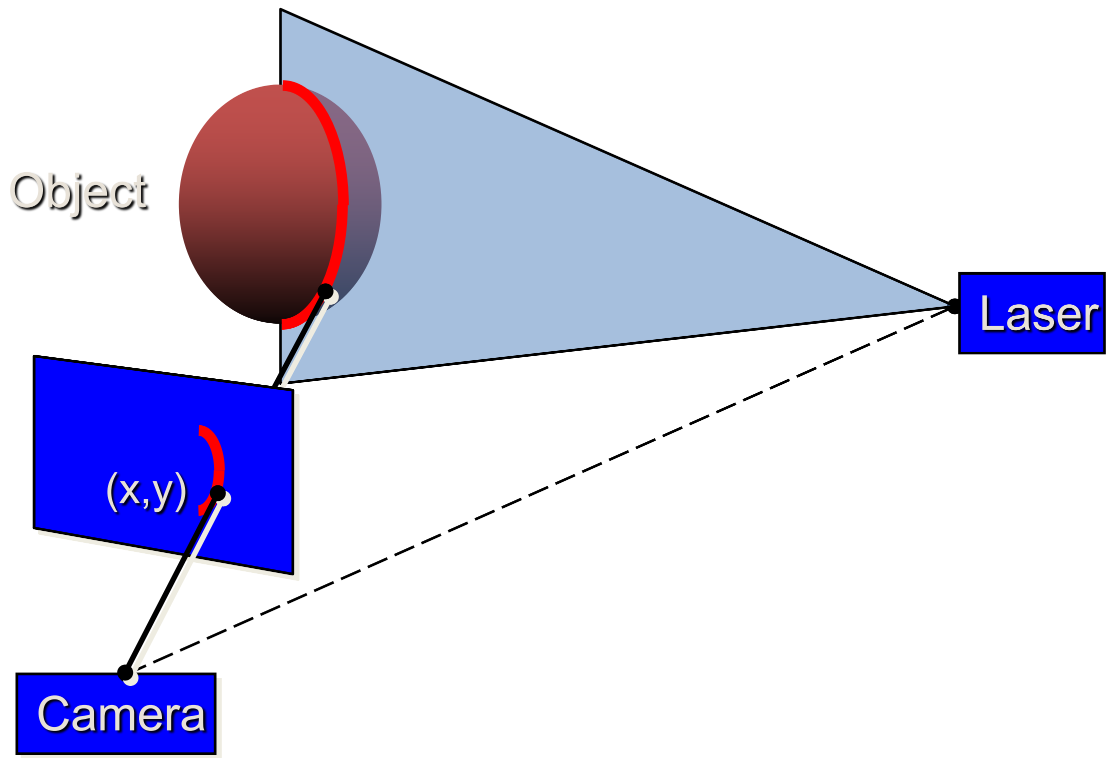
Real-Time 3D Model Acquisition Pipeline



Real-Time 3D Model Acquisition Pipeline



Recall Triangulation…



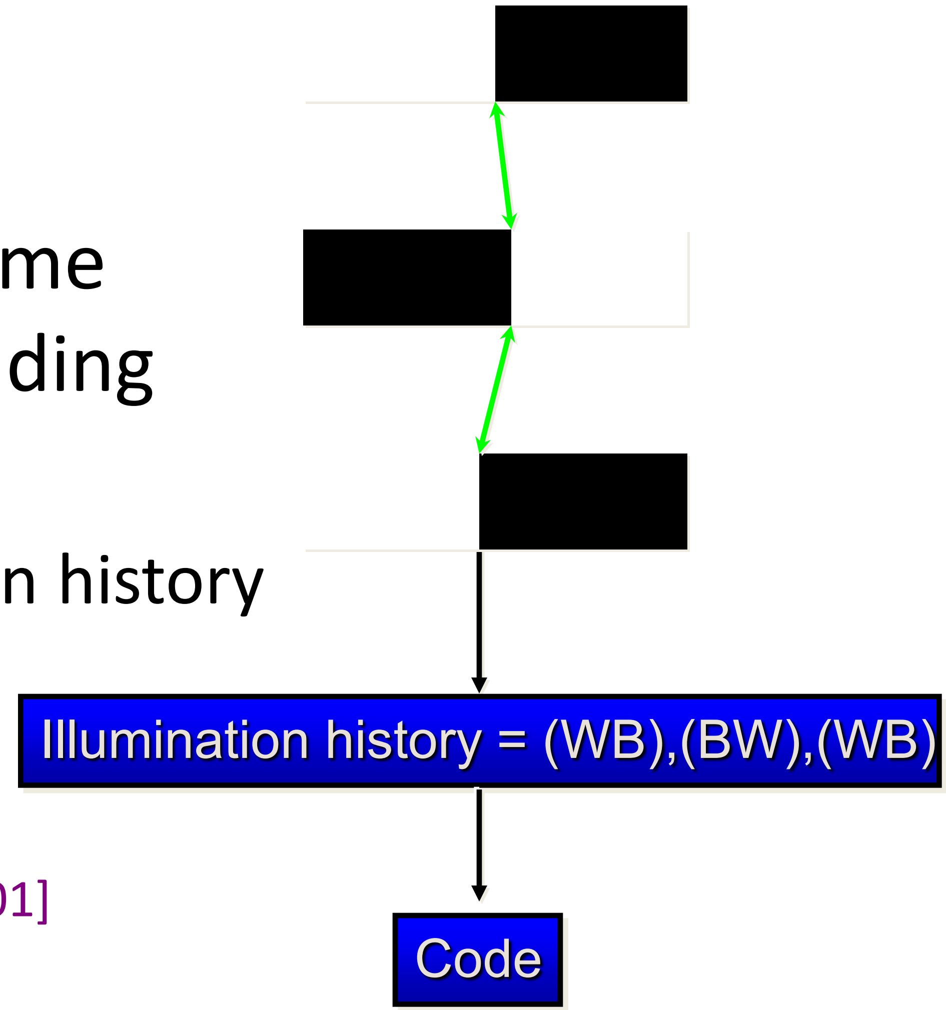
- Depth from ray-plane triangulation

Recall Triangulation…

- Faster acquisition: project multiple stripes
- Correspondence problem: which stripe is which?

Codes for Moving Scenes

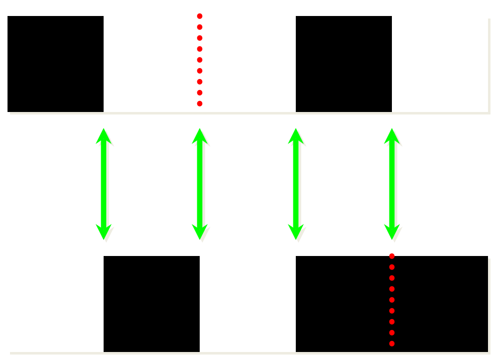
- Assign time codes to stripe boundaries
- Perform frame-to-frame tracking of corresponding boundaries
  - Propagate illumination history



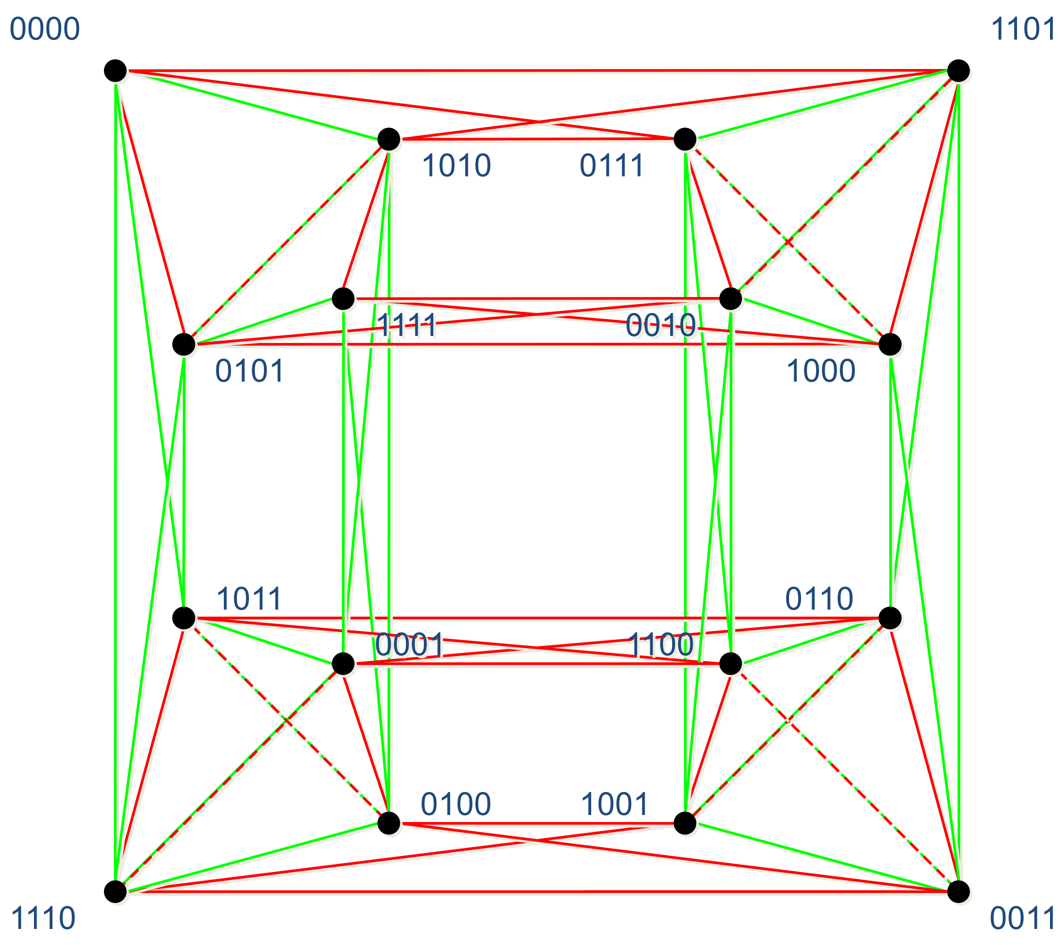
[Hall-Holt & Rusinkiewicz, ICCV 2001]

Designing a Code

- Want many "features" to track:
  lots of black/white edges at each frame
- Try to minimize ghosts – WW or BB
  "boundaries" that can't be seen directly

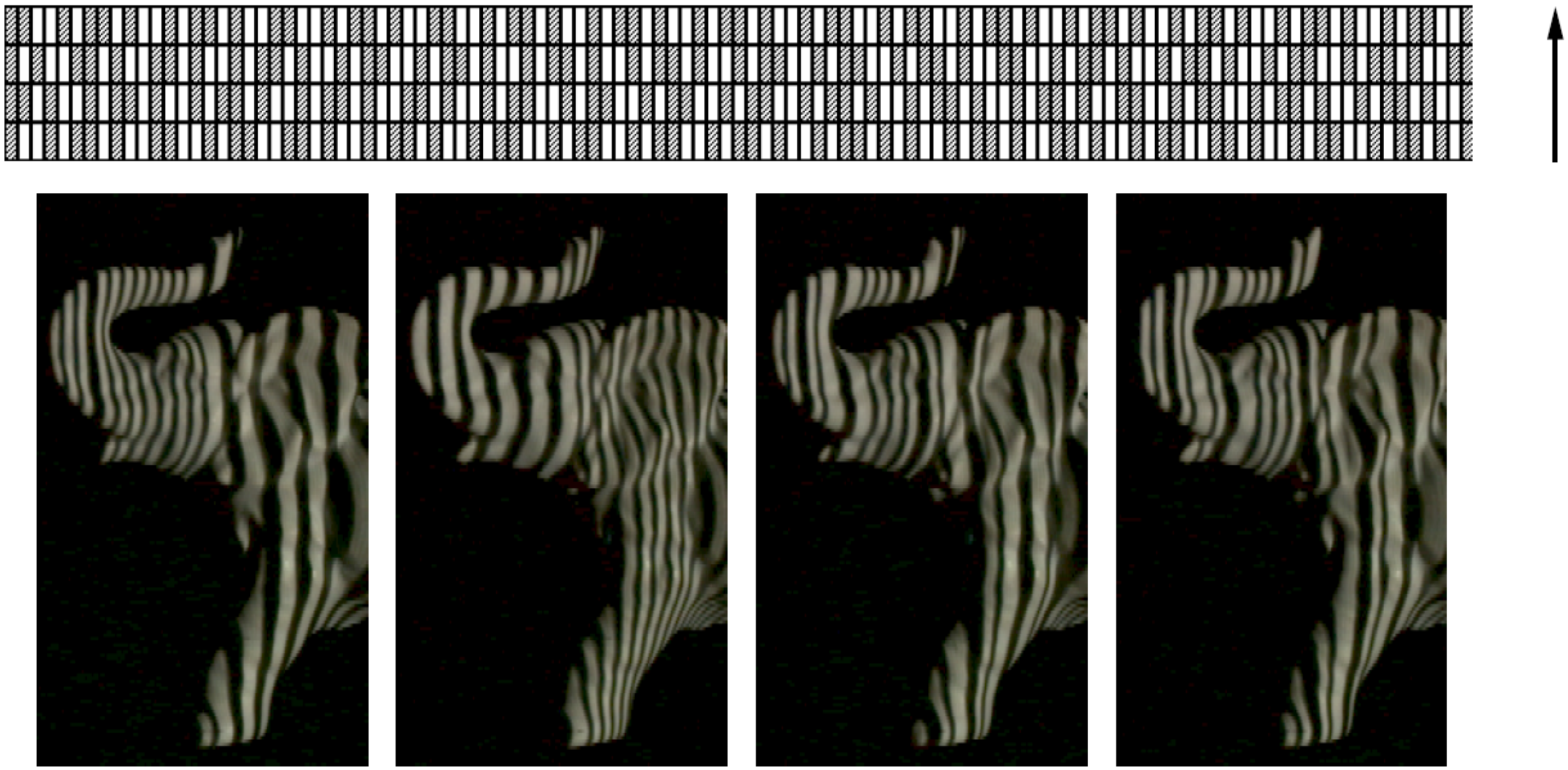


Designing a Code



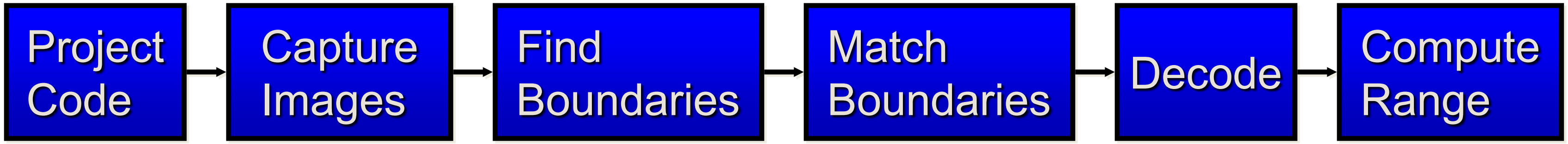
[Hall-Holt & Rusinkiewicz, ICCV 2001]

Space-Time Boundary Code



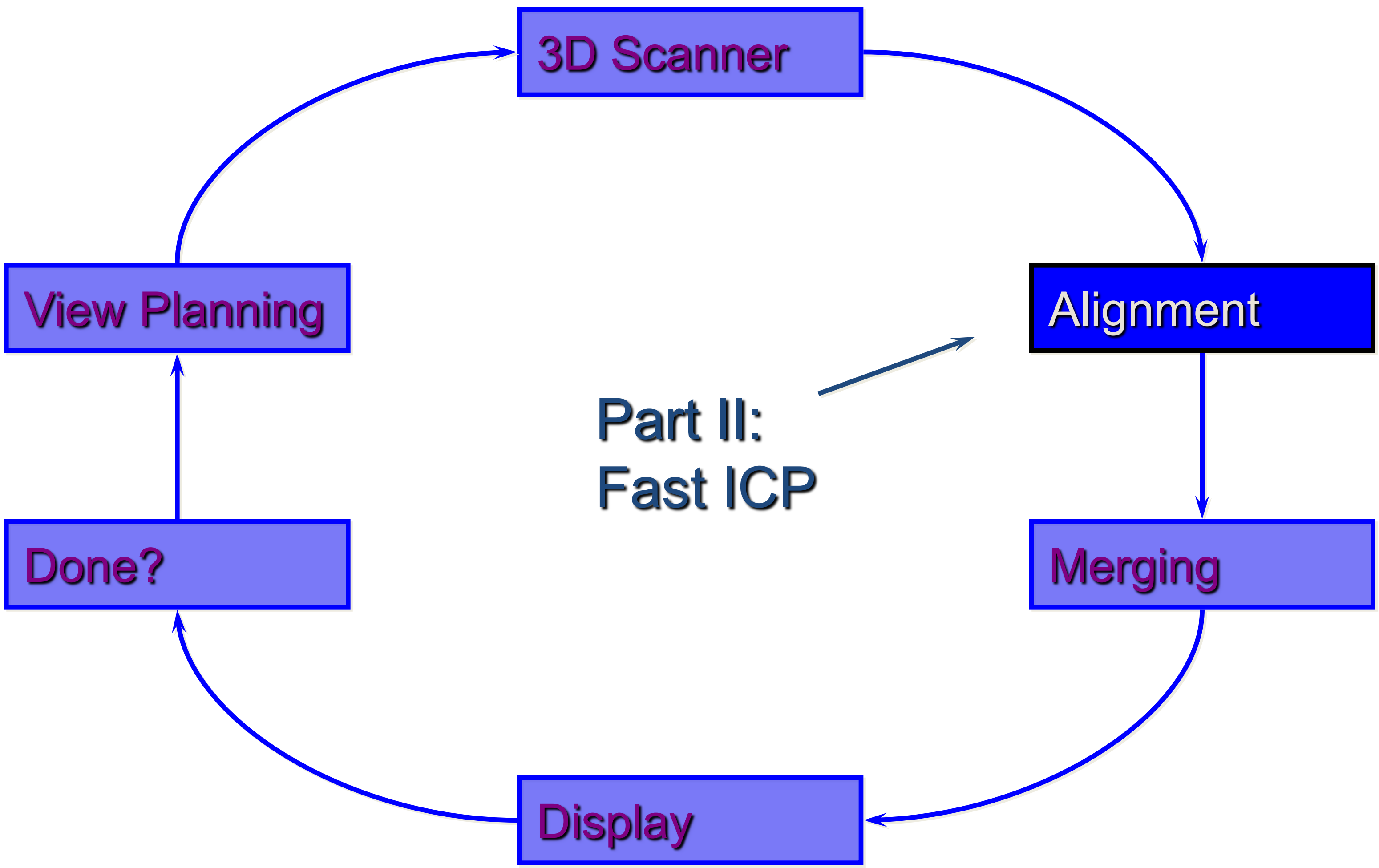
Implementation

- Pipeline:



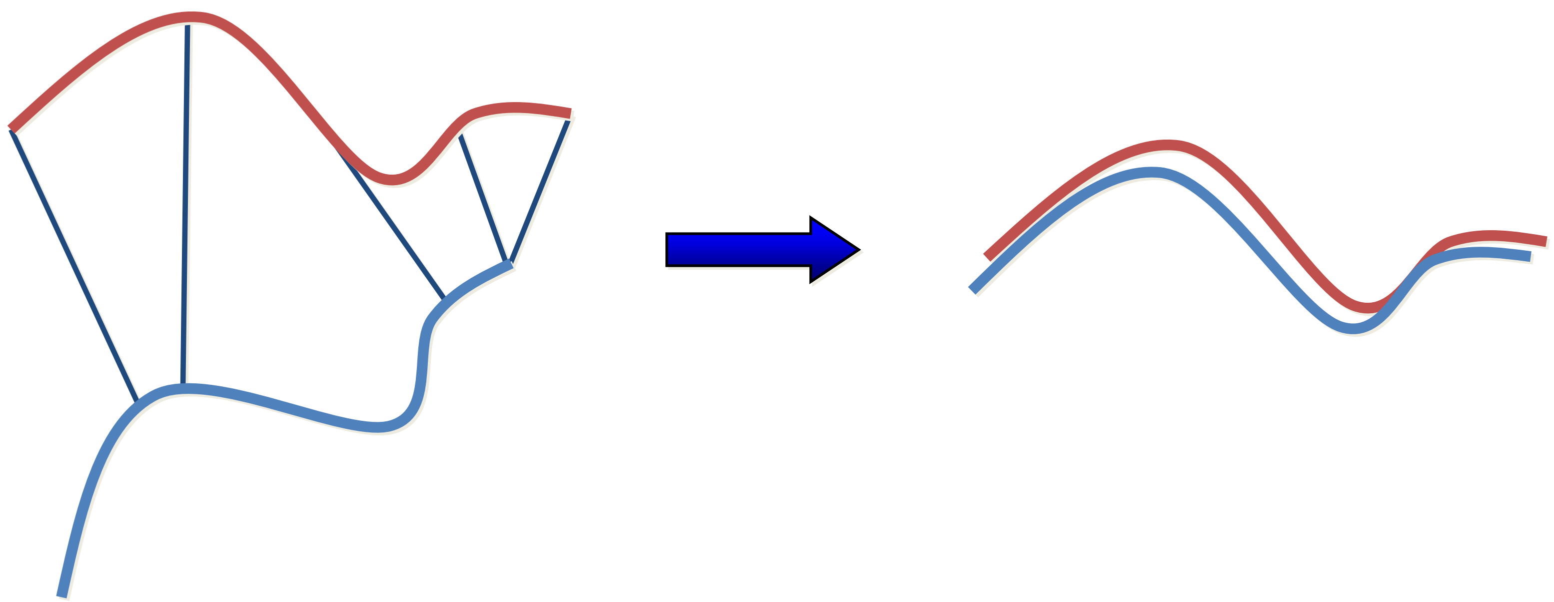
- DLP projector illuminates scene @ 60 Hz.
- Synchronized NTSC camera captures video
- Pipeline returns range images @ 60 Hz.

Real-Time 3D Model Acquisition Pipeline



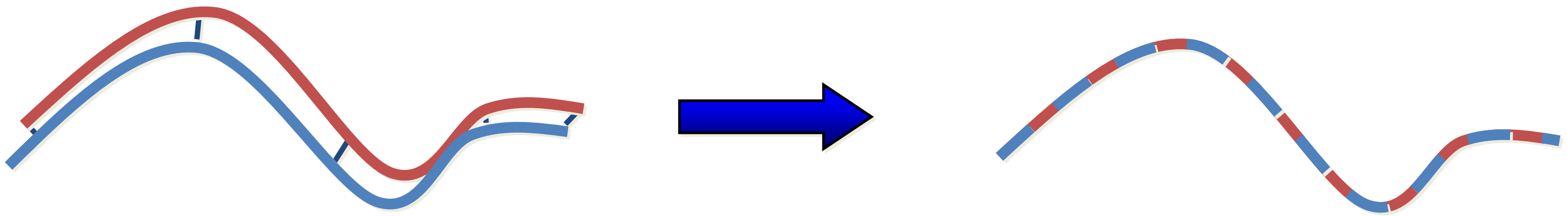
Aligning 3D Data

- ICP (Iterative Closest Points): for each point on one scan, minimize distance to closest point on other scan…



Aligning 3D Data

- … and iterate to find alignment
  - Iterated Closest Points (ICP) [Besl & McKay 92]

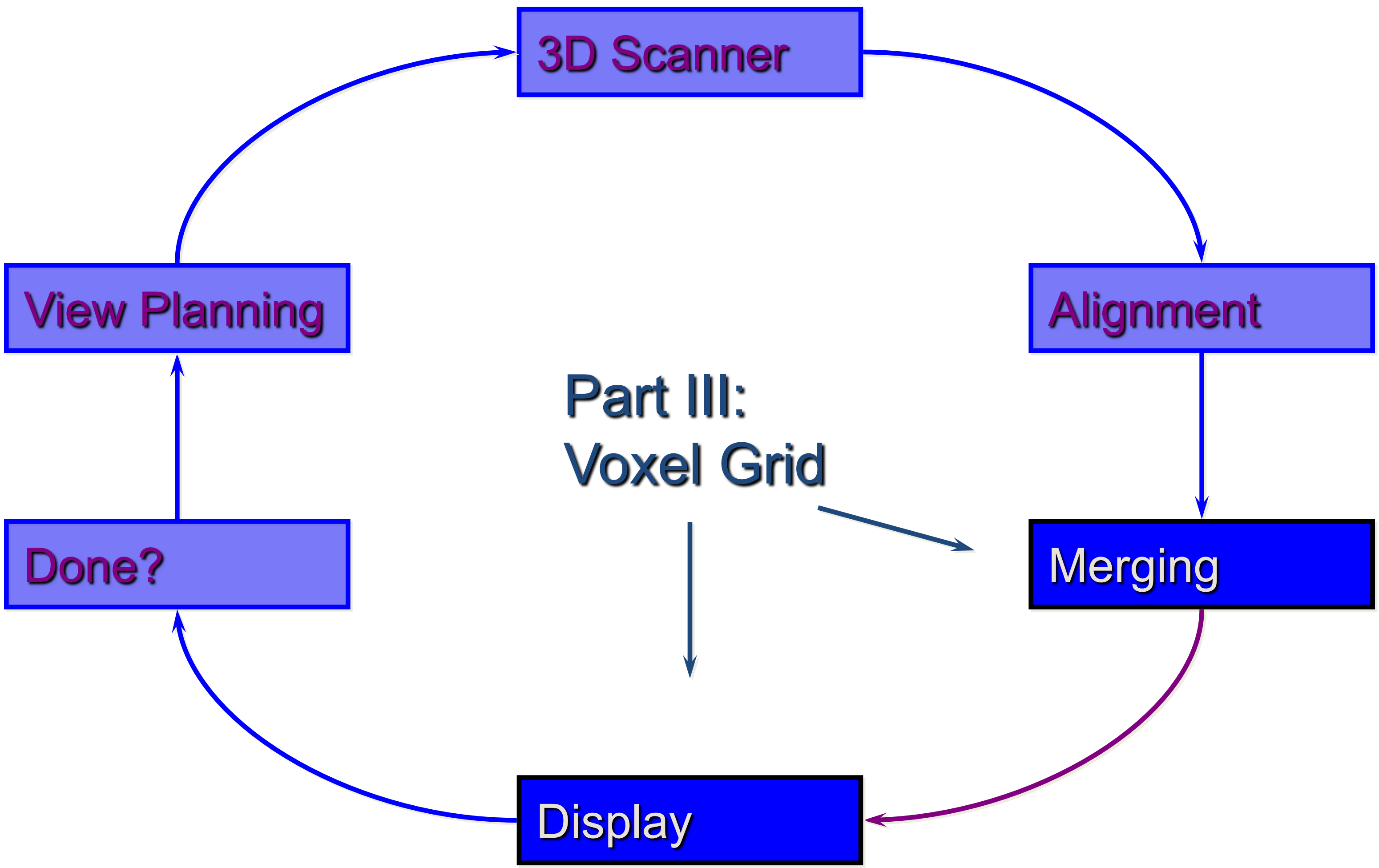


ICP in the Real-Time Pipeline

- Potential problem with ICP: local minima
  - In this pipeline, scans close together
  - Very likely to converge to correct (global) minimum
- Basic ICP algorithm too slow (~ seconds)
  - Point-to-plane minimization
  - Projection-based matching
  - With these tweaks, running time ~ milliseconds

[Rusinkiewicz & Levoy, 3DIM 2001]

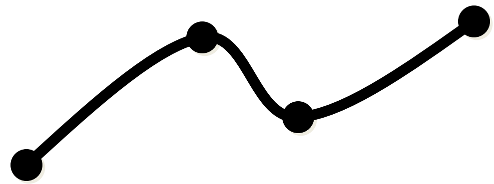
Real-Time 3D Model Acquisition Pipeline



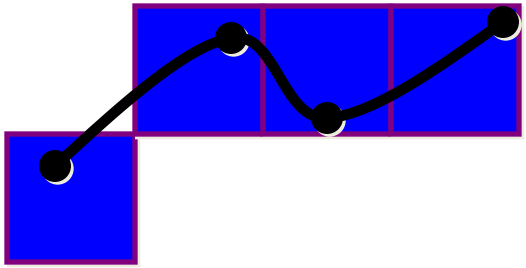
Merging and Rendering

- Goal: visualize the model well enough to be able to see holes
- Cannot display all the scanned data – accumulates linearly with time
- Standard high-quality merging methods: processing time ~ 1 minute per scan

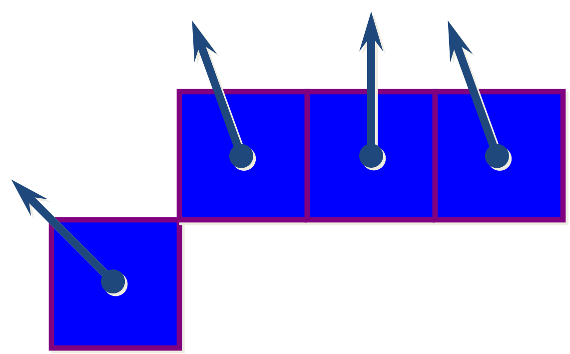
Merging and Rendering



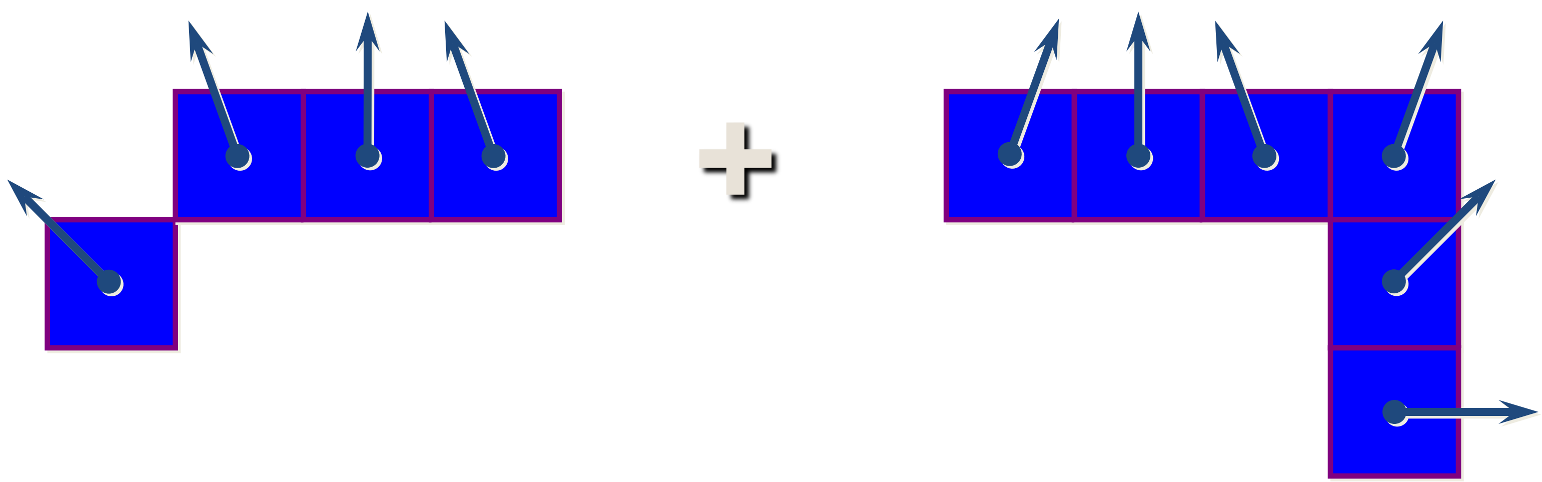
Merging and Rendering



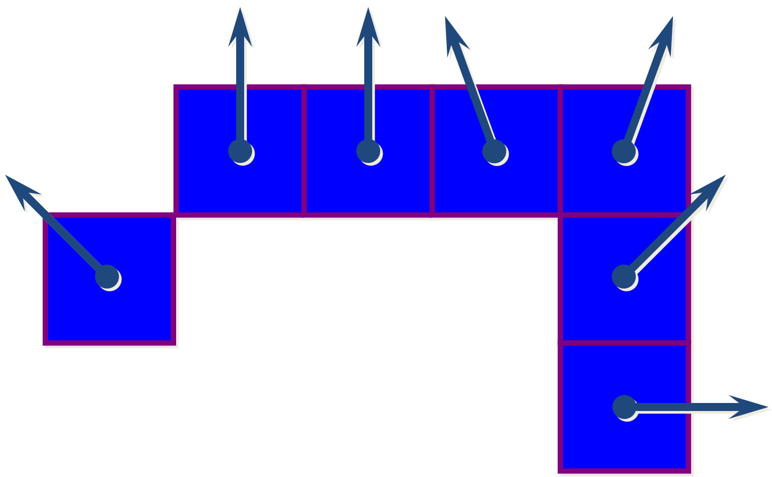
Merging and Rendering



Merging and Rendering



Merging and Rendering



- Point rendering, using accumulated normals for lighting

Example: Photograph

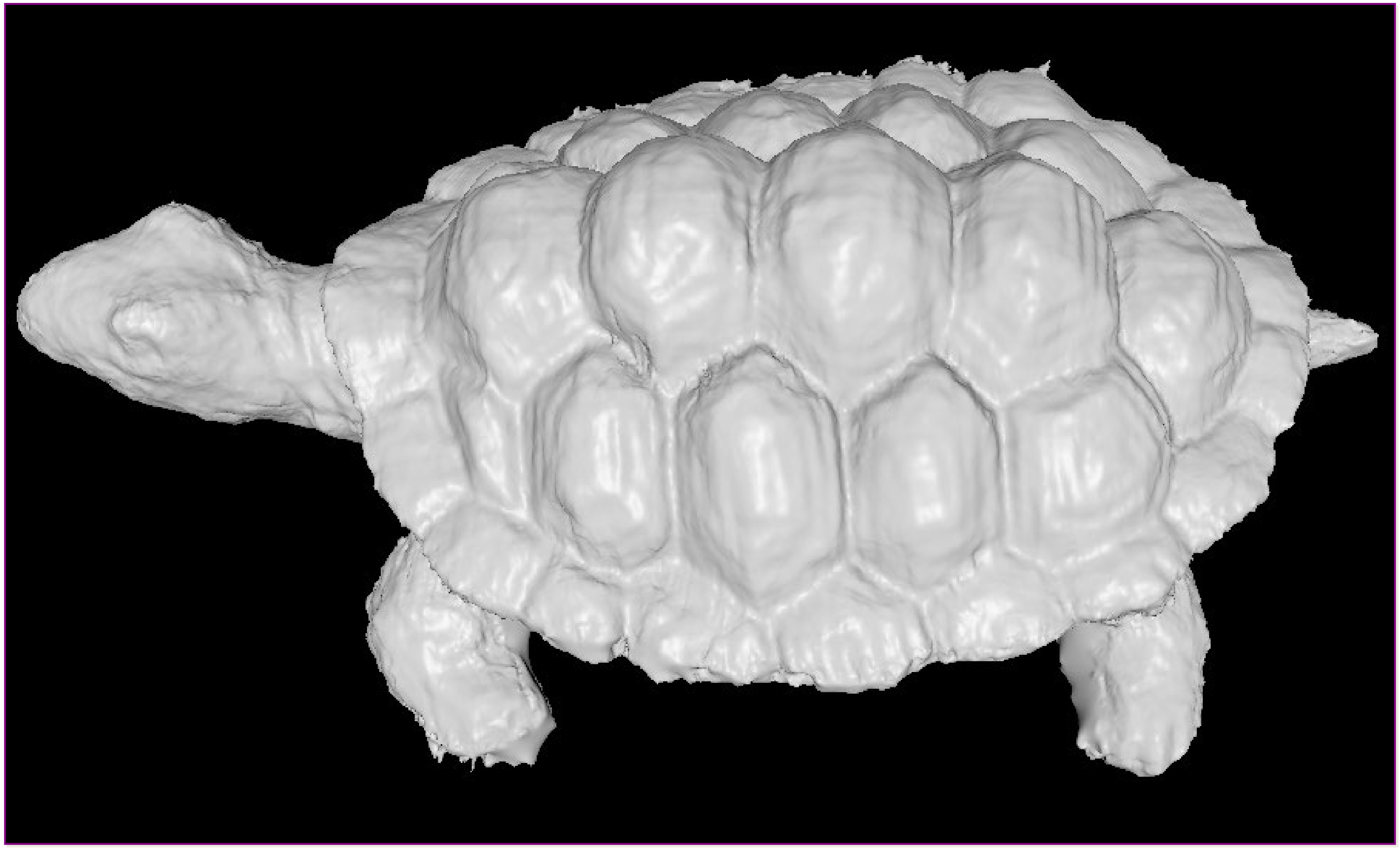
18 cm.

Result

Postprocessing

- Real-time display
  - Quality/speed tradeoff
  - Goal: let user evaluate coverage, fill holes
- Offline postprocessing for high-quality models
  - Global registration
  - High-quality merging (e.g., using VRIP [Curless 96])

Postprocessed Model



Fast 3D Scanning with Automatic Motion Compensation

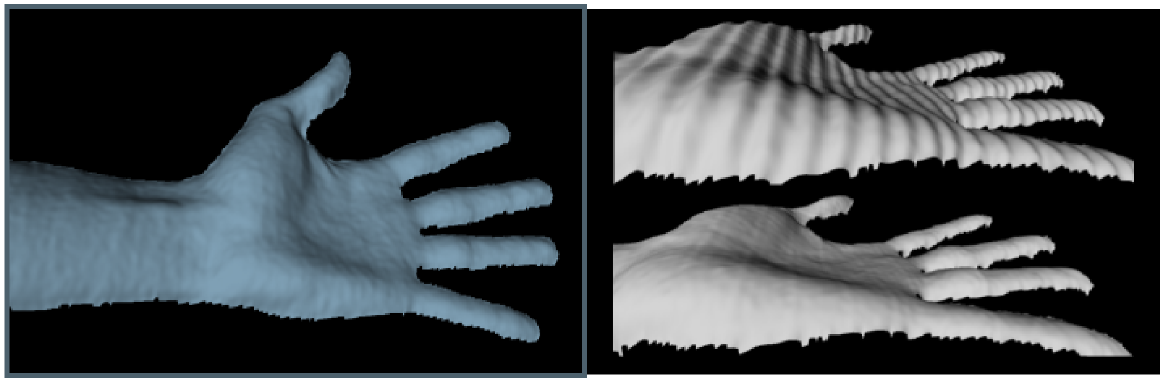


Figure 1. 3D reconstructions of a static (left) and a moving (right) hand. Motion compensation (bottom right) removes the ripples from the reconstructed surface (top right).

- Higher resolution/quality than previous method
- Uses phase-shifting and motion-compensation

Fast 3D Scanning with Automatic Motion Compensation

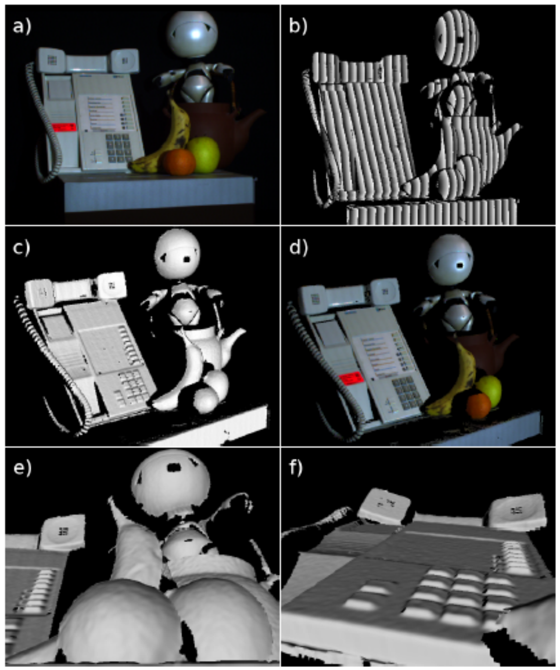


Figure 7. Reconstruction of a complex scene containing several objects (phone, teapot, figure, fruit): a) texture image, b) reconstructed phase, c) geometry, d) textured geometry, e)+f) close-ups

Figure 8. Reconstruction of a waving cloth. Motion correction correctly removes the ripples (right).

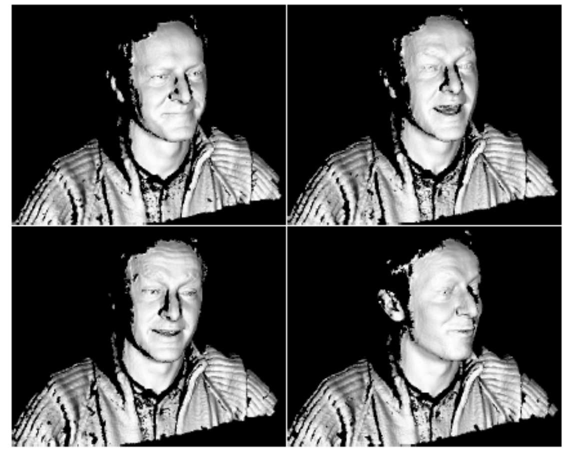


Figure 9. Reconstruction of a person speaking.

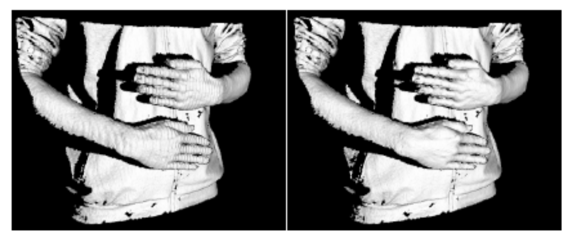


Figure 10. Reconstruction of moving hands in front of the torso. On the right with motion compensation.

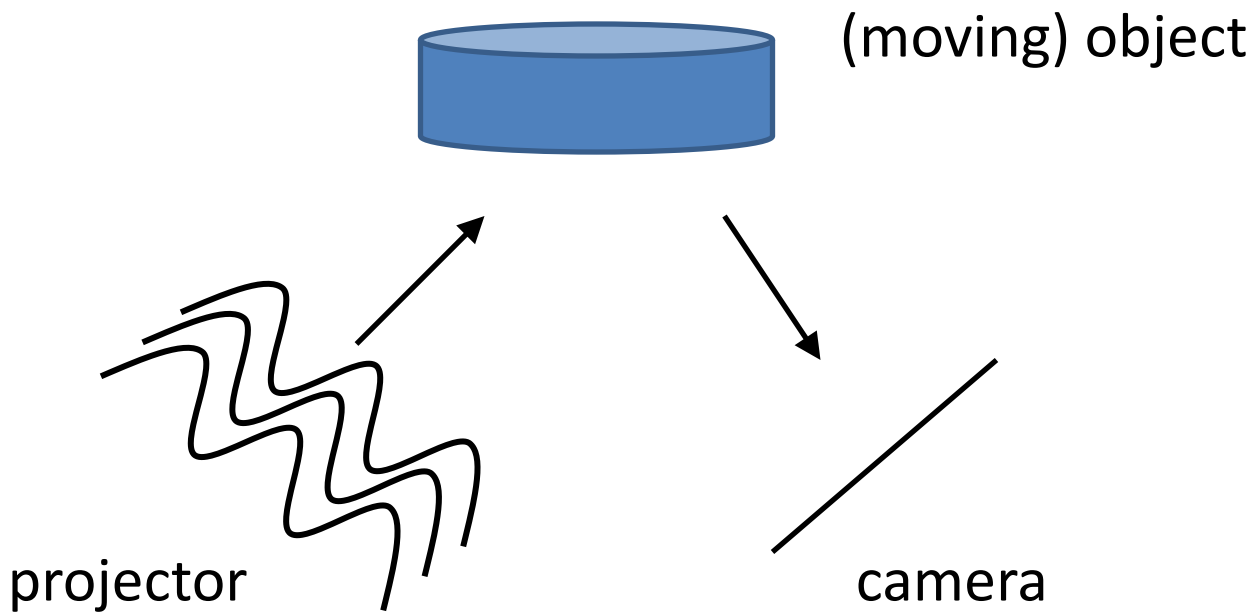
Figure 11. Online reconstruction of hand gestures.

Motion Compensation

- Since phase shifting assumes a static scene, **correlation-based stereo** is used to compensate for motion

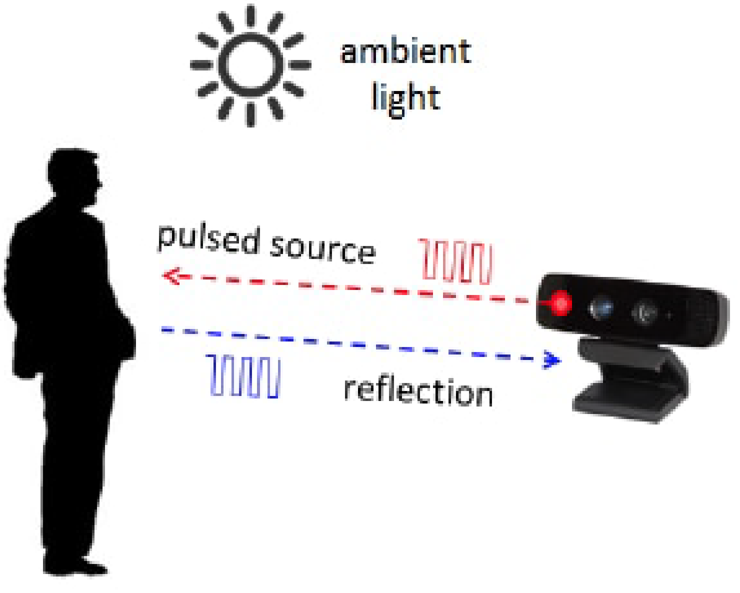
- An additional modification is proposed to **handle discontinuities** (which also plague standard phase shifting)

Motion Compensation



RGBD Cameras

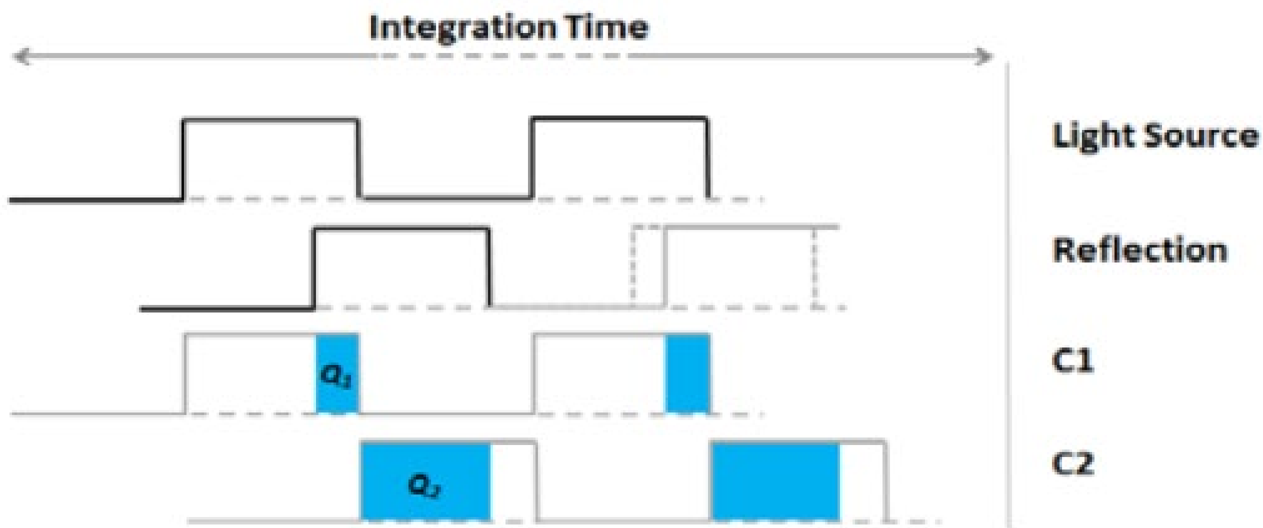
- Capture RGB + D
- For example:
  - TOF (Time of Flight Cameras)



TOF Cameras

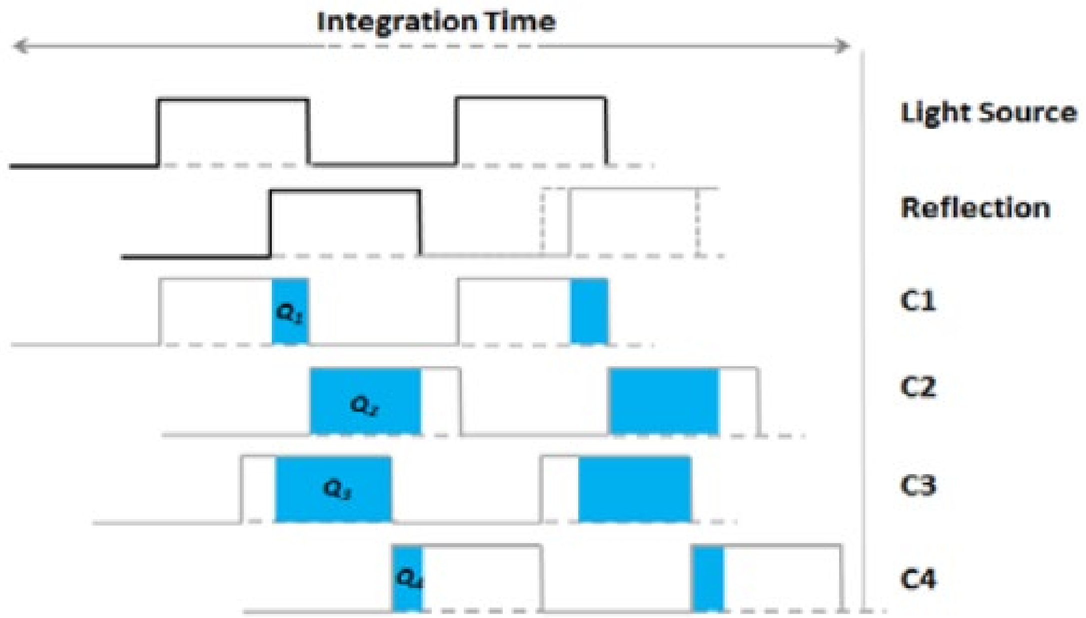
- Older (initial?) versions:
  - Swiss Ranger
  - Zcam
    - From 3DV, then bought by Microsoft
  - Kinect
    - Version 1: used infra-red structured light
    - Version 2: used TOF (from Zcam?)

TOF Pulsed Concept



$$d = \frac{1}{2} c \Delta t \left(\frac{Q_2}{Q_1 + Q_2}\right) \quad \text{(per pixel)}$$

TOF Continuous Wave Concept



$$\phi = \arctan\left(\frac{Q_3 - Q_4}{Q_1 - Q_2}\right) \qquad \text{(per pixel)}$$

$$d = \frac{c\Delta t}{2\pi}\phi$$

Time Resolution

- Single light pulse for 100m -> 660ns
- Typically 1ms for a full round trip acquisition

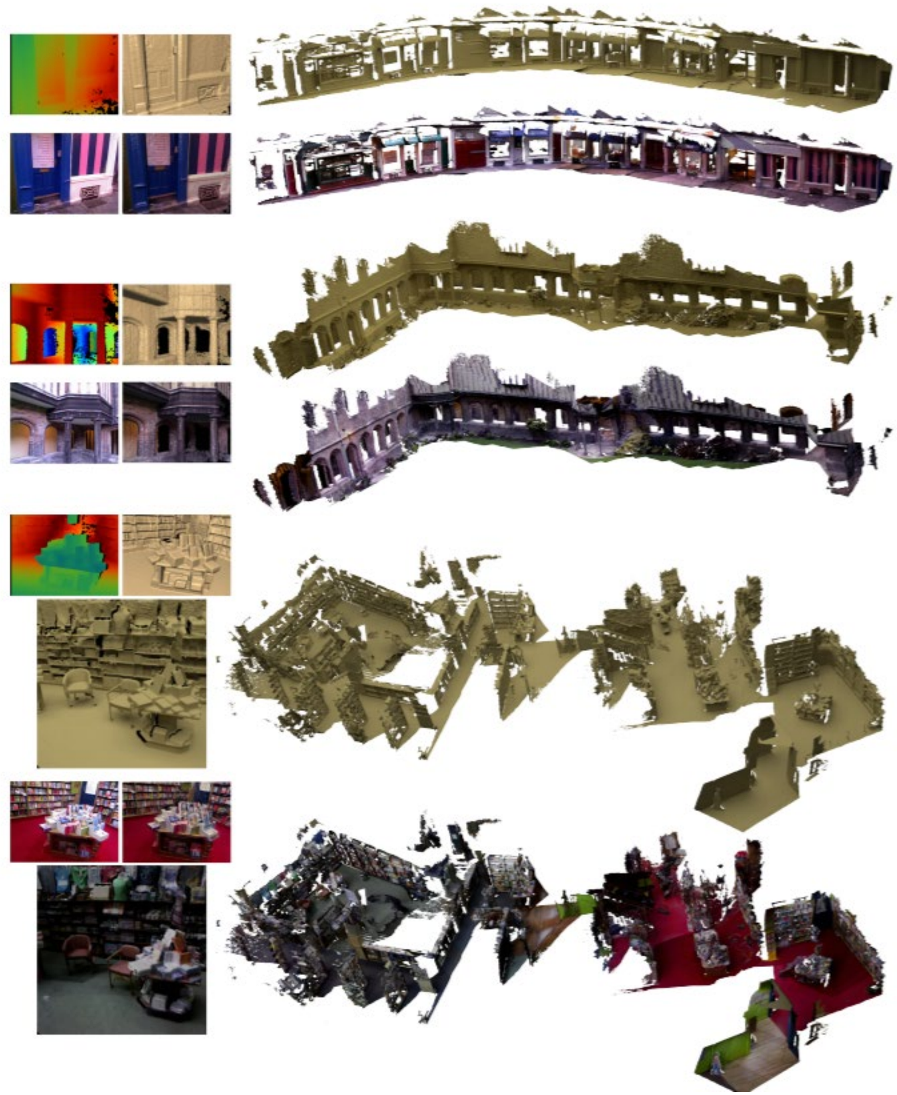
SPAD

- Single Photon Avalanche Diodes
  - Detect and count photons
- What is a photon?
  - "Photons are massless particles that can move no faster than the speed of light measured in vacuum. The photon belongs to the class of boson particles"
- https://www.dgp.toronto.edu/projects/ultra-wideband/

Real-time 3D Reconstruction at Scale using Voxel Hashing

Niessner et al. 2013 (TOG)

Real-time 3D Reconstruction at Scale using Voxel Hashing



Real-time 3D Reconstruction at Scale using Voxel Hashing

https://www.youtube.com/watch?v=XD_UnuWSaoU

Real-time Non-Rigid Reconstruction using an RGB-D Camera

[Zollhoefer et al. 2015]

Real-time Non-Rigid Reconstruction using an RGB-D Camera

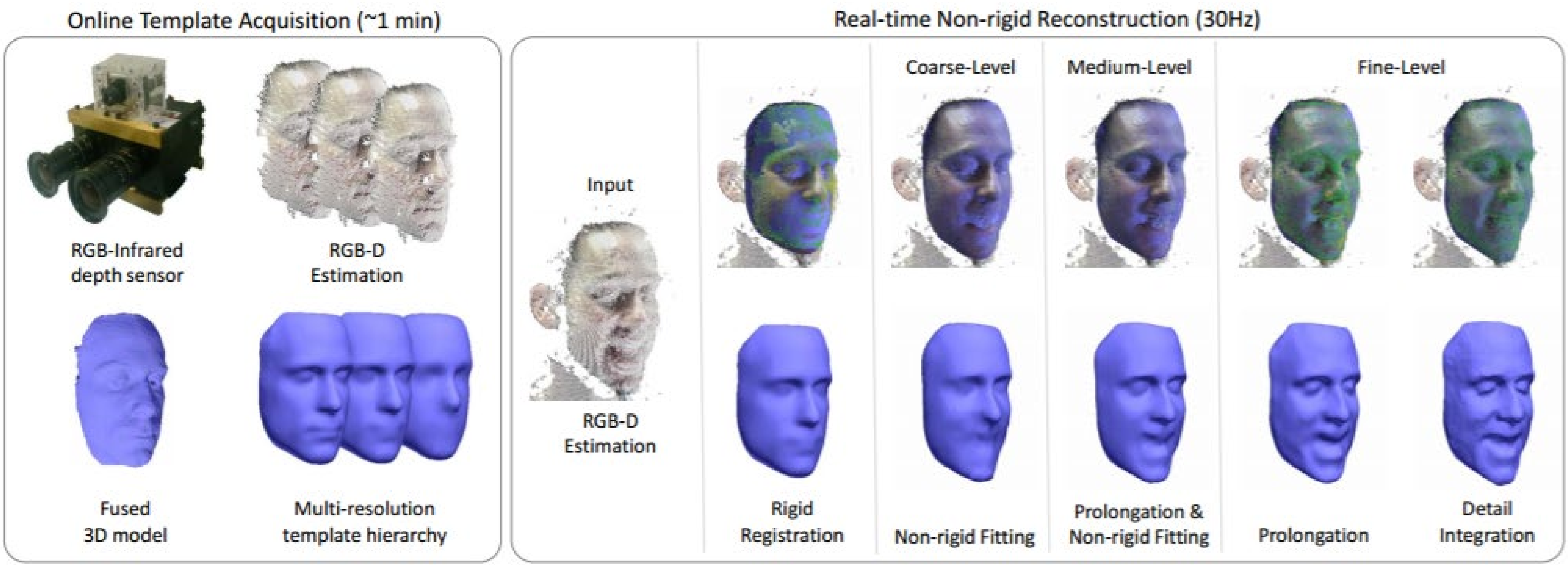


Figure 2: *Main system pipeline.* **Left:** *the initial template acquisition is an online process. Multiple views are volumetrically fused, and a multi-resolution mesh hierarchy is precomputed for the tracking phase.* **Right:** *in the tracking phase, each new frame is rigidly registered to the template, and a sequence of calls to the GPU-based Gauss-Newton optimizer is issued from coarse to fine mesh resolution. At the finest resolution, detail is integrated using a thin-plate spline regularizer on the finest mesh.*

Real-time Non-Rigid Reconstruction using an RGB-D Camera

https://www.youtube.com/watch?v=qNiPirnvMHc