Optimal Decoding of Stripe Patterns with Window Uniqueness Constraint

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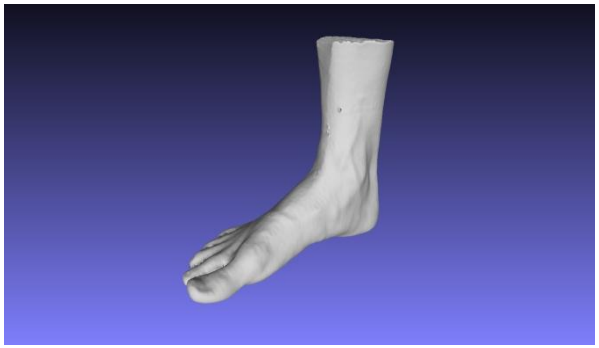
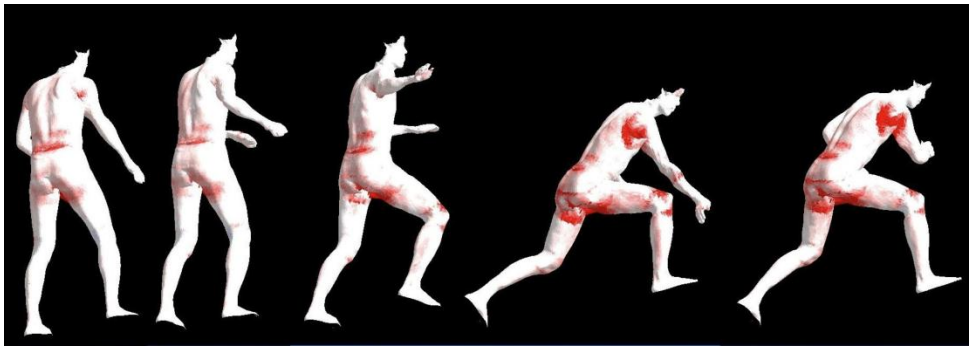
One-shot depth acquisition

- Structured Light for Moving Objects





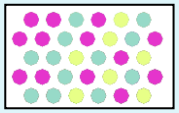
Spatially-Coded Illumination

- 1D Discrete
  - De Bruijn sequence

[Hugli 1989] [Zhang 2002]
[Lim 2009] [Yamazaki 2011]

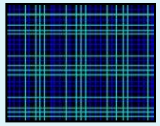
Dense & Robust

- 2D Discrete
  - M-array



[Griffin 1992] [Morano 1998]
[Pages 2006] [Kinect]

  - Non-formal



[Maruyama 1995]
[Forster 2007] [Sagawa 2012]
[Kawasaki 2008]

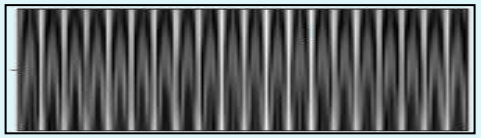
Very Robust
Sparse

- Continuous
  - Phase-shifting

[Wust 1991]
[Guan 2004]

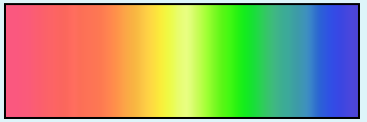
  - Frequency-multiplexing

[Takeda 1983] [Gdeisat 2006]
[Berryman 2008] [Zhang 2008]
[Wu 2006] [Cobelli 2009]



  - Spatial multiplexing

[Carrihill 1985] [Tajima 1990]



Subpixel
Sensitive

Taxonomy by [Salvi 2010]

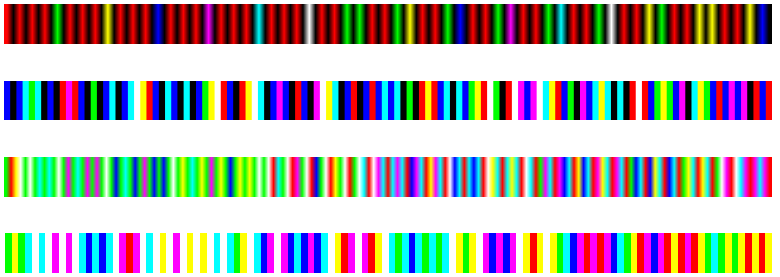
De Bruijn Color Code

- De Bruijn sequence B(*k*, *n*)
  - Cyclic sequence
  - Composed of symbols with size *k*
  - Unique subsequence of length *n*

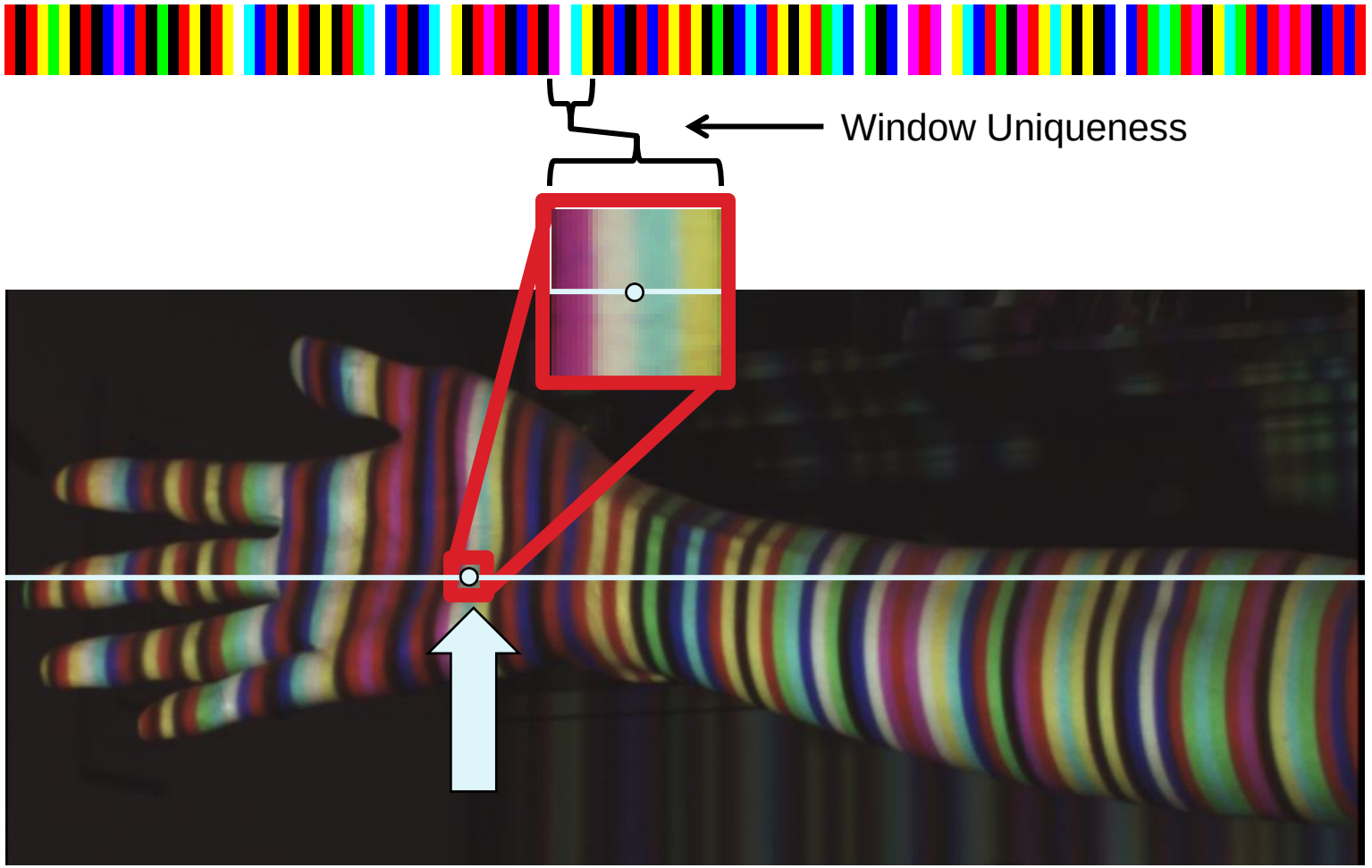
B(5,3)={…,2,0,0,3,0,0,4,0,1,1,0,1,2,0,1,3,0,1,4,0,2,…}

Window Uniqueness Property

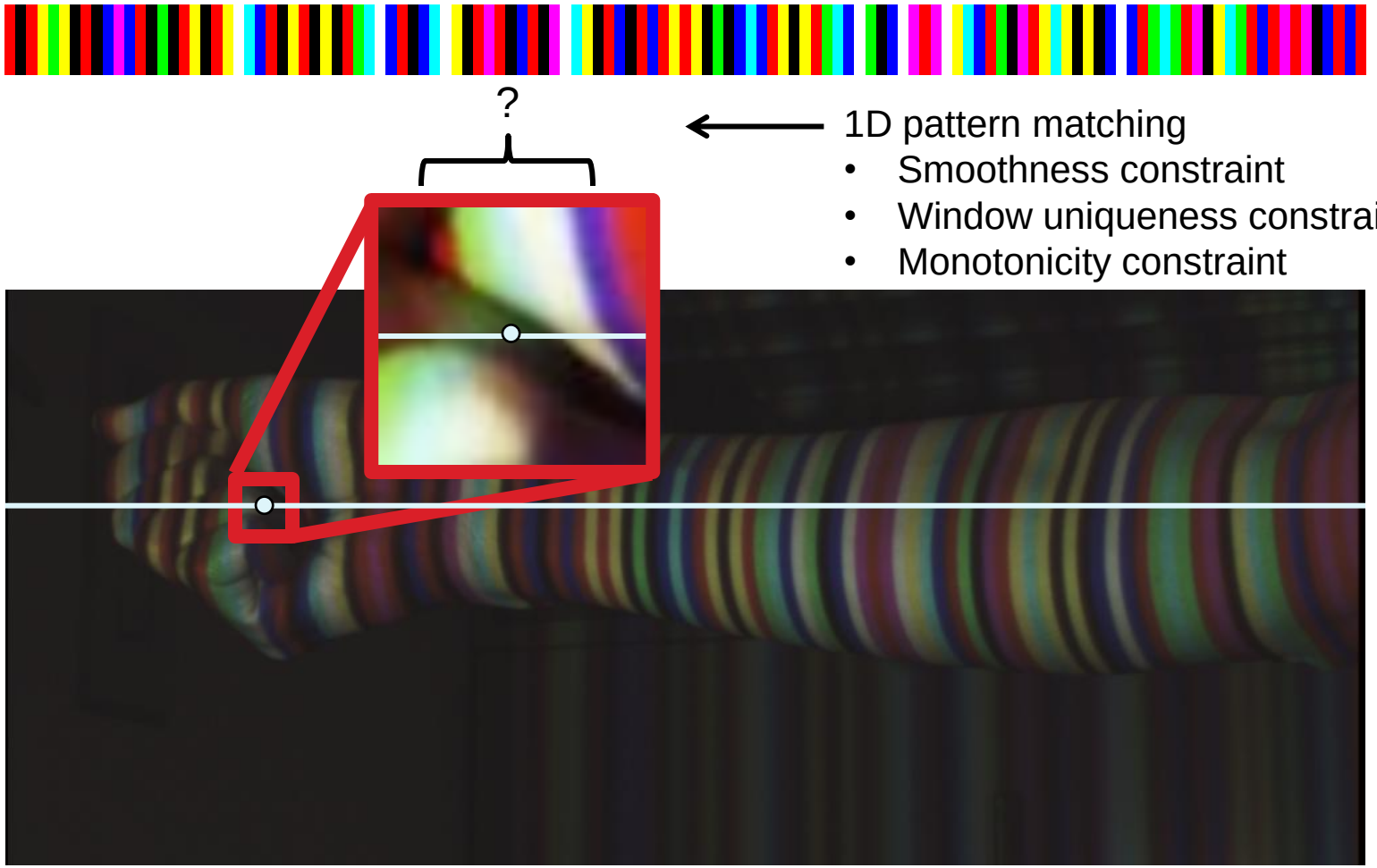
- Color Stripes
  - Direct [Hugli 1989]
  - XOR [Zhang 2002]
  - Non-recurring [Lim 2009]
  - Hamming [Yamazaki 2011]



Decoding Structured Light



Decoding Structured Light

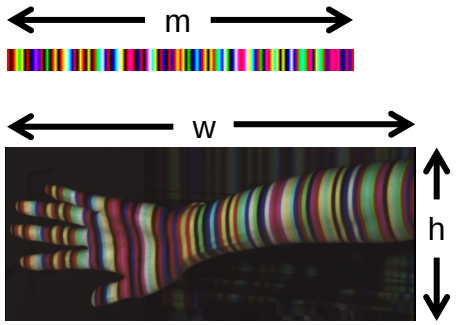


Decoding Structured Light

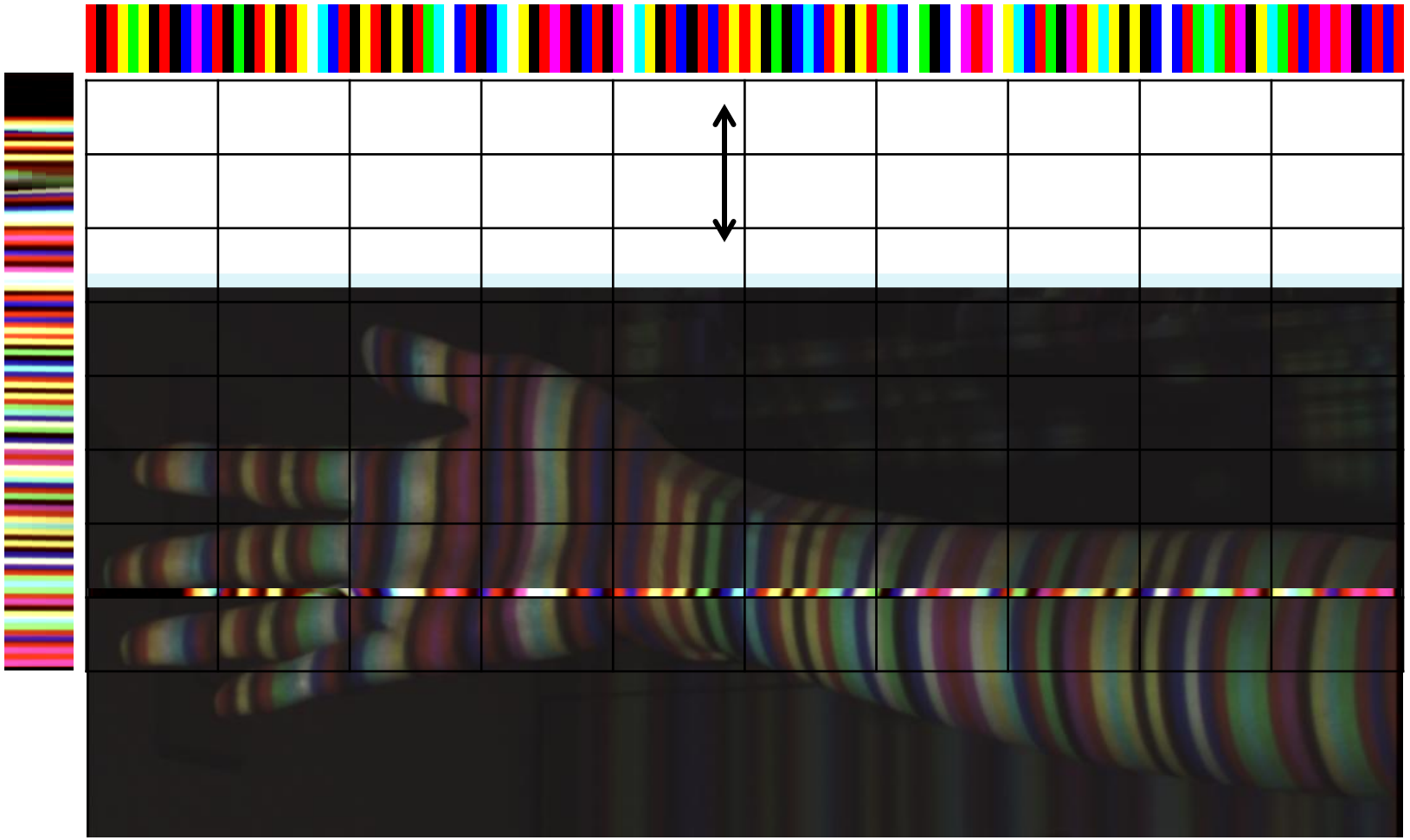
- Global optimization
  - Annealing, Graph-cut, Belief propagation, etc.
  - High computational cost
  - Convergence not guaranteed

- Greedy search
  - propagates local reconstruction [Forster 2006]
  - sometimes yields better results than the global methods [Schmalz 2010]
  - 10+ FPS by CPU implementation

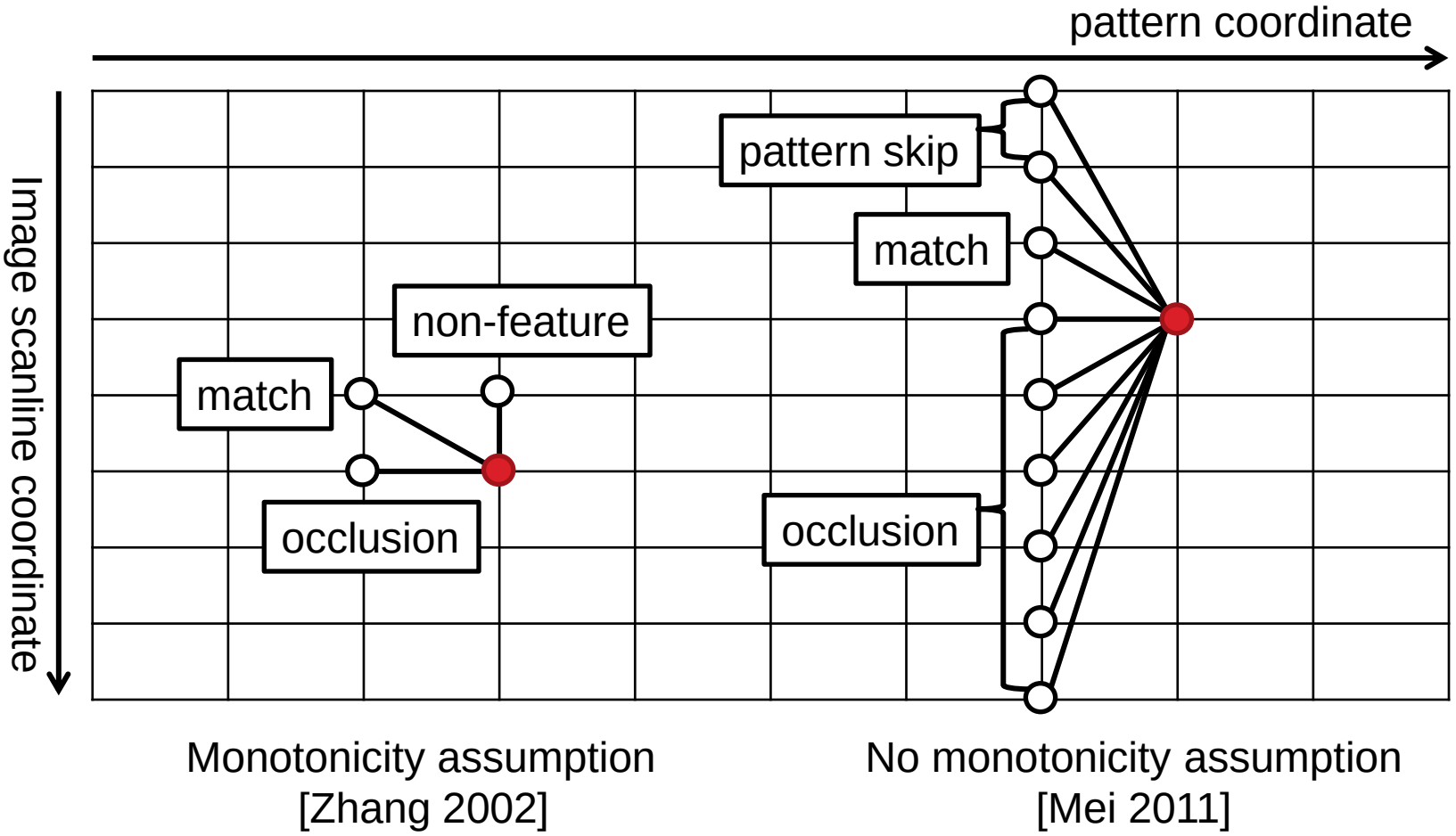
- Dynamic Programming Matching (DPM)
  - Optimal, pseudo linear algorithm : O(whm)
  - Monotonicity assumption
    - Multipass DP [Zhang 2002] : O(whm)
    - Non-monotonic DP [Mei 2011] : $O(w^2hm)$
  - 60+ FPS by GPU implementation [Yamazaki 2011]



Dynamic Programming



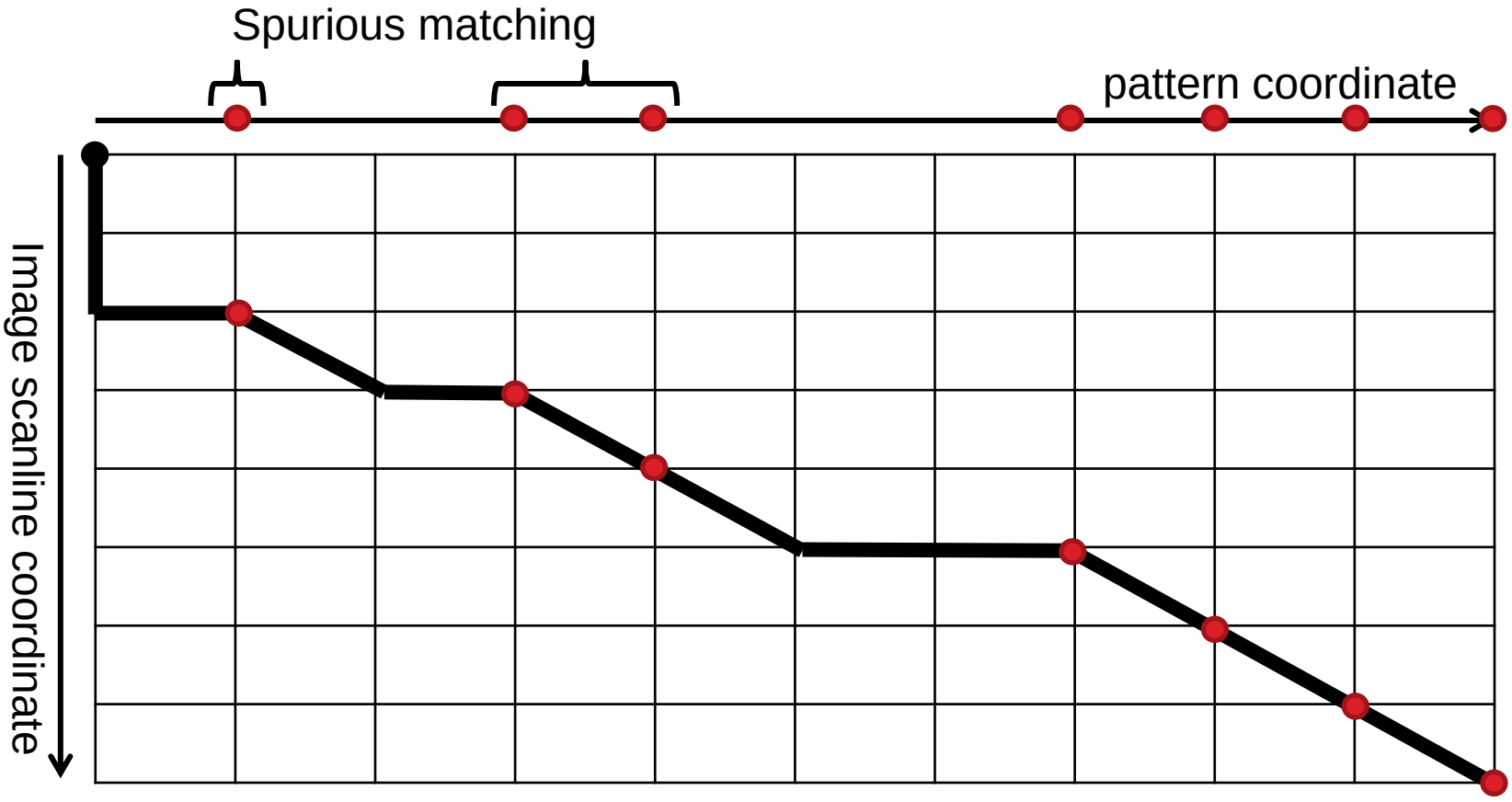
Dynamic Programming



Monotonicity assumption
[Zhang 2002]

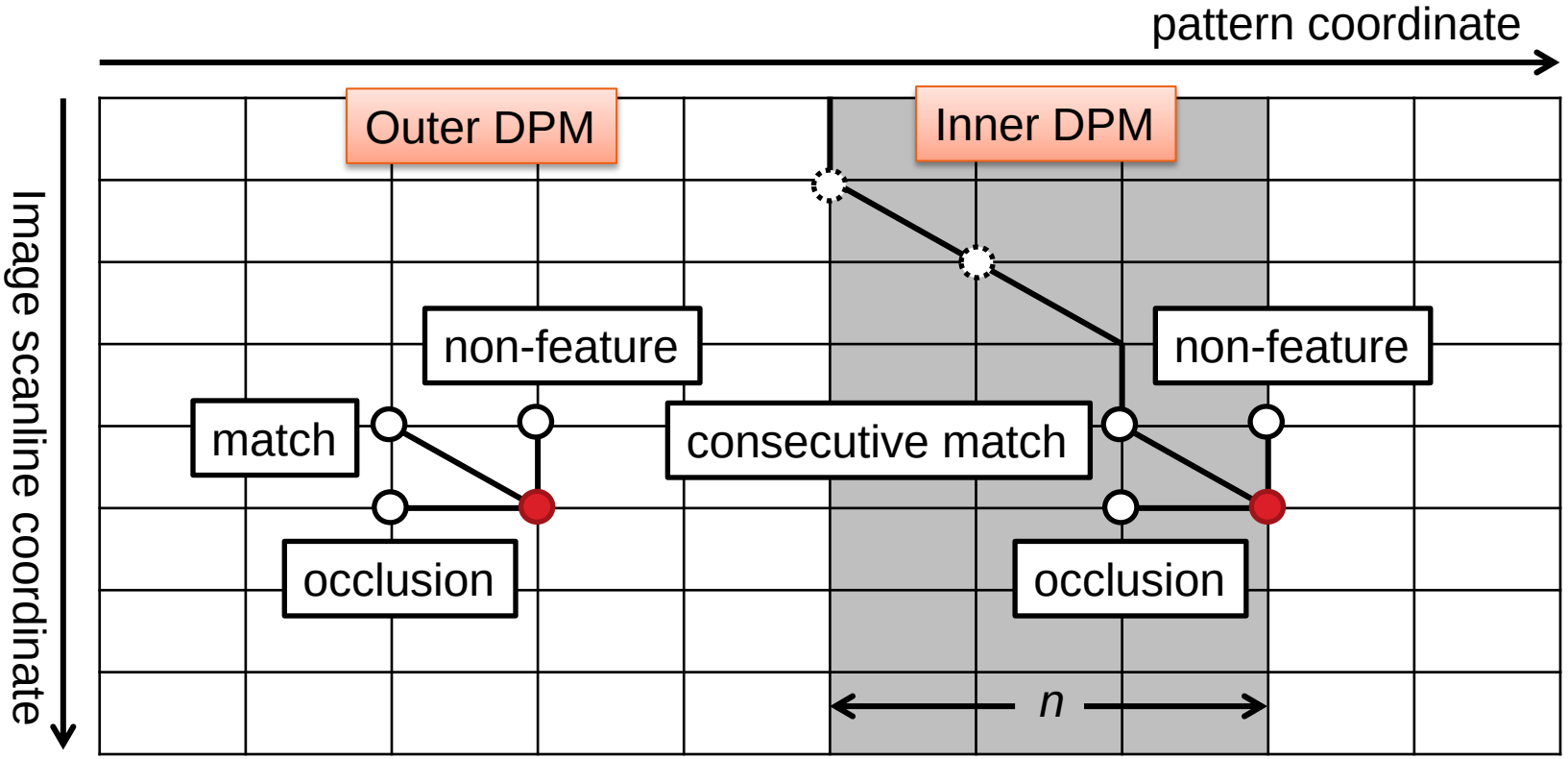
No monotonicity assumption
[Mei 2011]

Backtracking



No window uniqueness constraint

Proposed DPM



Monotonicity assumption

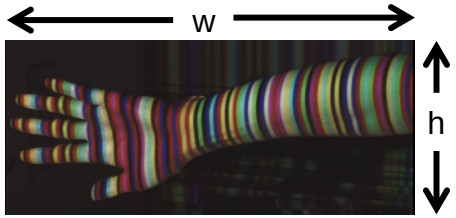
[Zhang 2002]

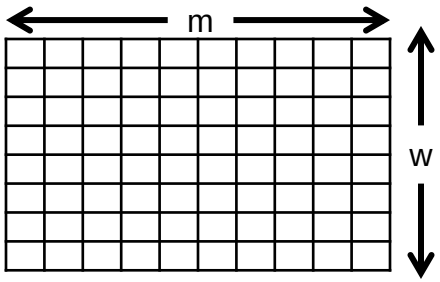
No monotonicity assumption
+ window uniqueness constraint
[Proposed]

Computational Complexity

- For each scanline : h
  - Generate DPM table *T* : O(wm)
  - For each column r in T : m
    - Solve Inner DPM : O(w)
    - For each row r in c : w
      - Find the optimal solution : O(1)
  - Backtrack : O(w)

O(whm)

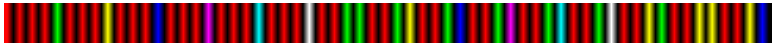




Same complexity as conventional DPM

Experiments

- Color Stripes based on De Bruijn sequences (n=4)
  - Direct [Hugli 1989]



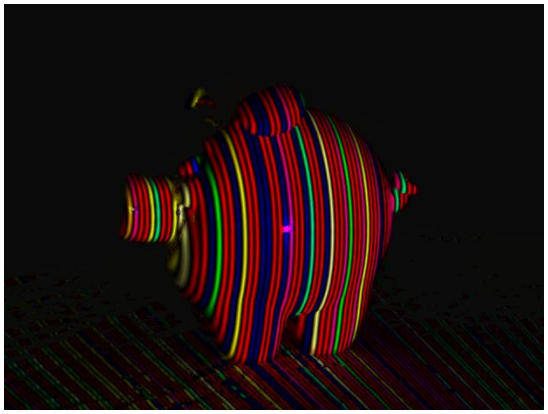
    - {1, …, 7} = {001, …, 111} = {red, …, white}
    - Black separators inserted
  - XOR [Zhang 2002]

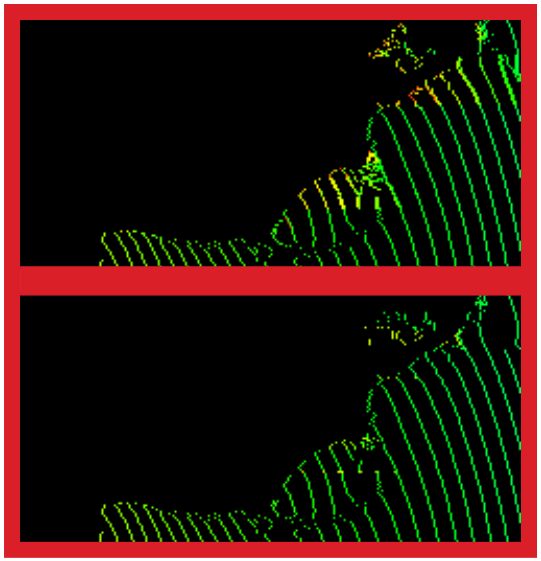
    - {1, …, 7} = {⊕001, …, ⊕111}
    - Encoded into stripe borders
  - Non-recurring [Lim 2009]

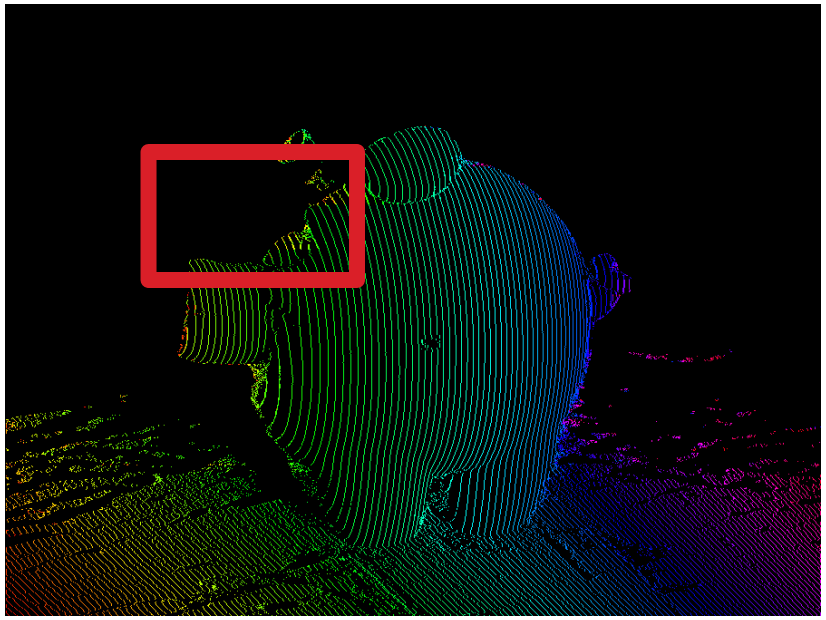
    - Eliminated consecutive symbols from a De Bruijn sequence
  - Hamming [Yamazaki 2011]

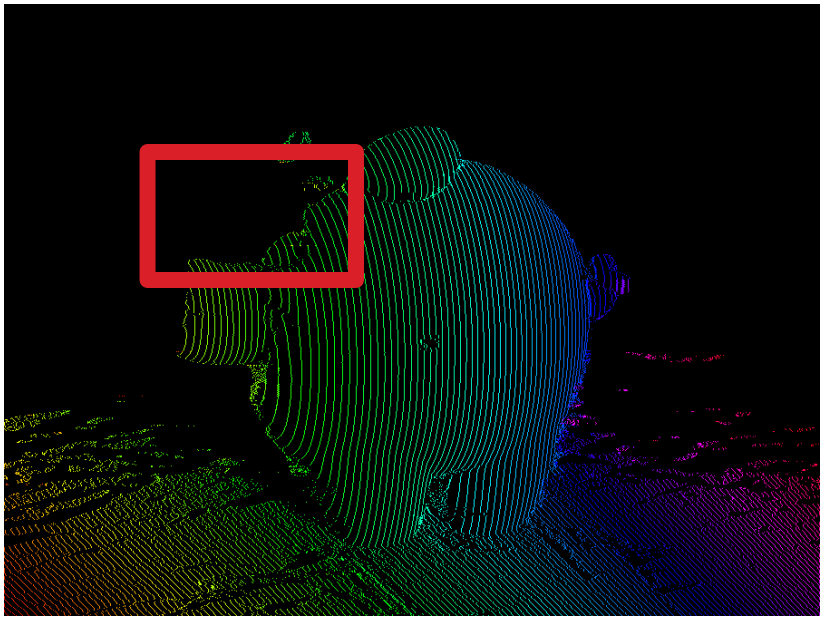
    - Eliminated simultaneous bit flips from a De Bruijn sequence

Result - Direct





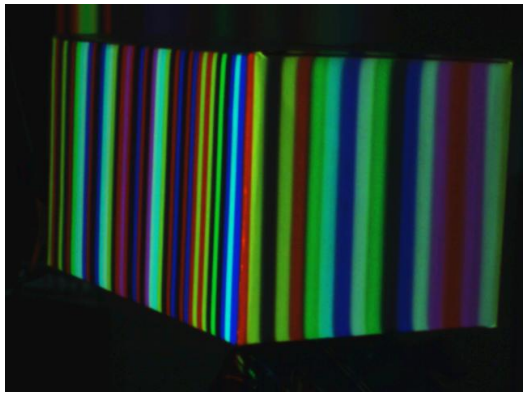


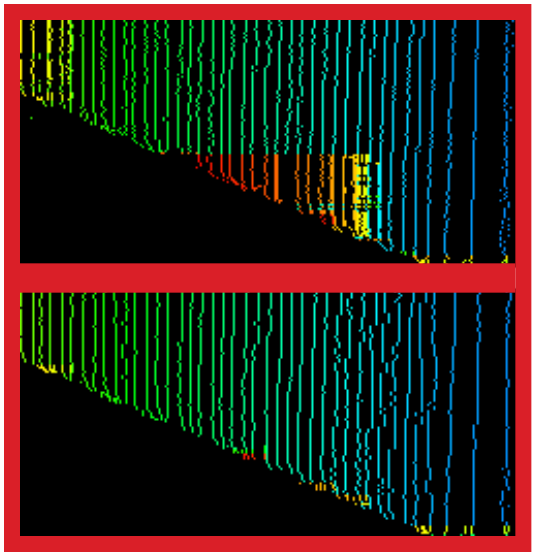


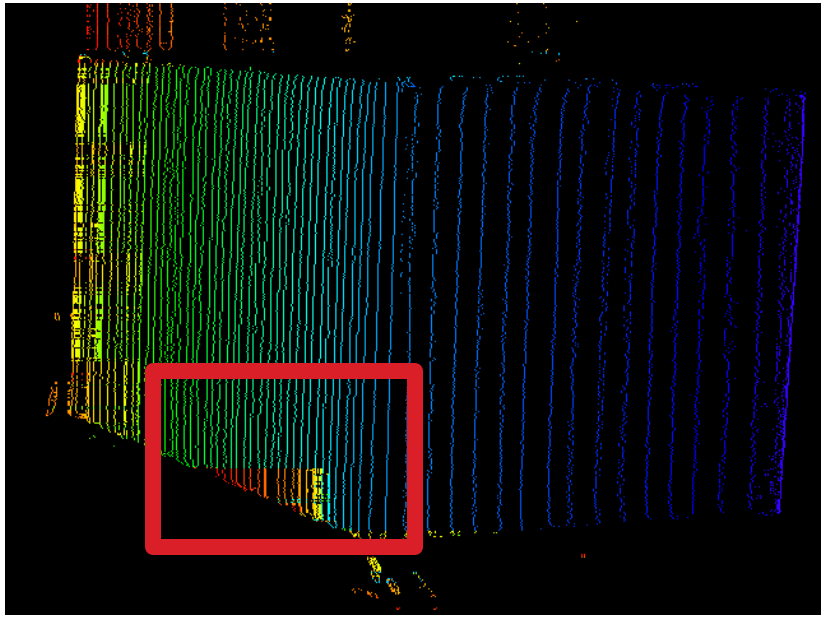
Conventional DPM

Proposed

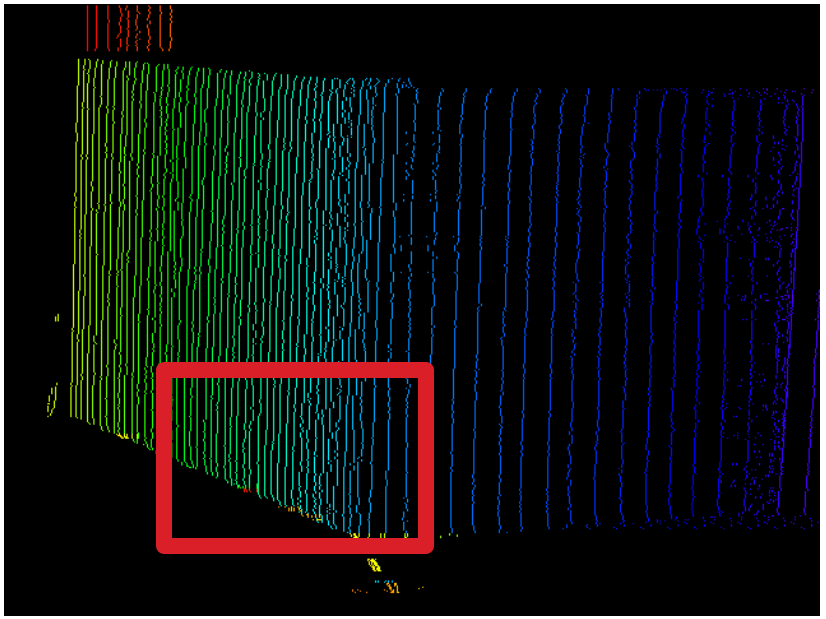
Result - XOR





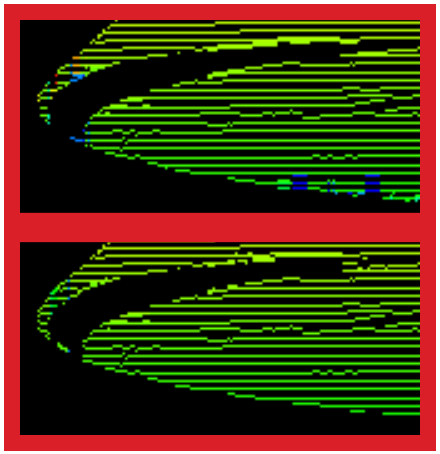


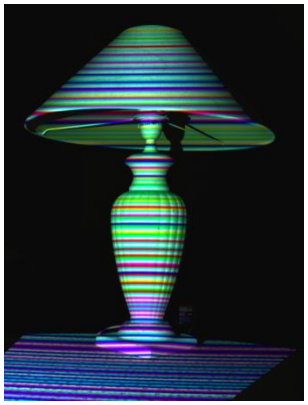
Conventional DPM

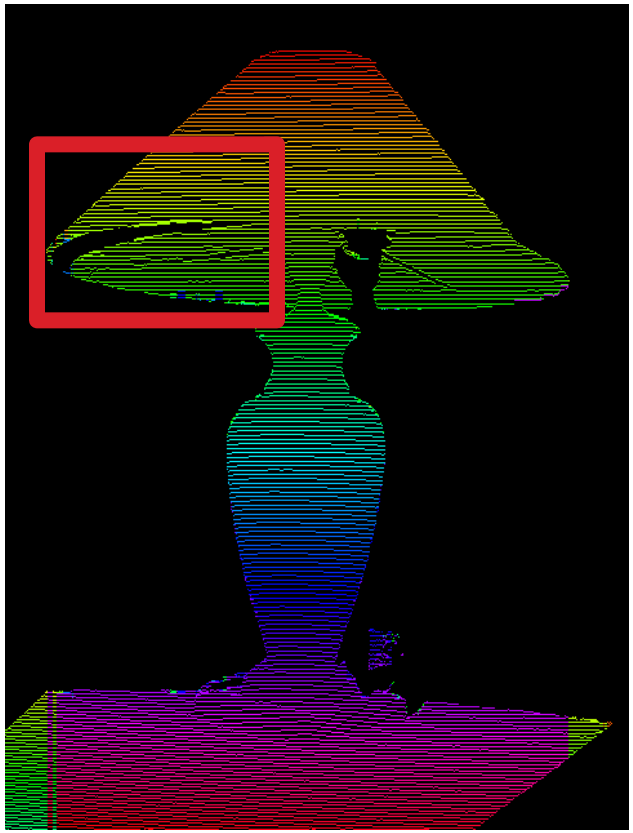


Proposed

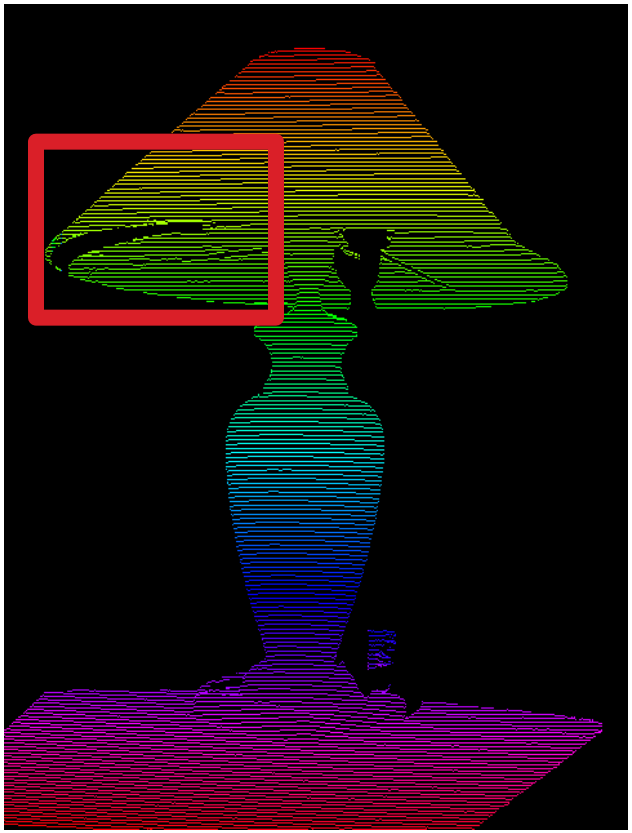
Result – Non-recurring





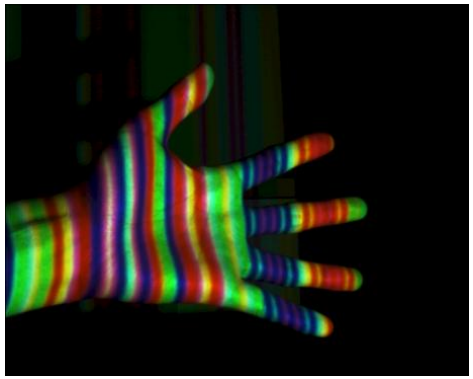


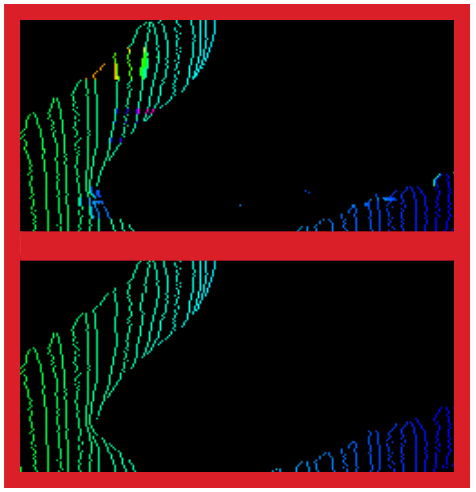
Conventional DPM

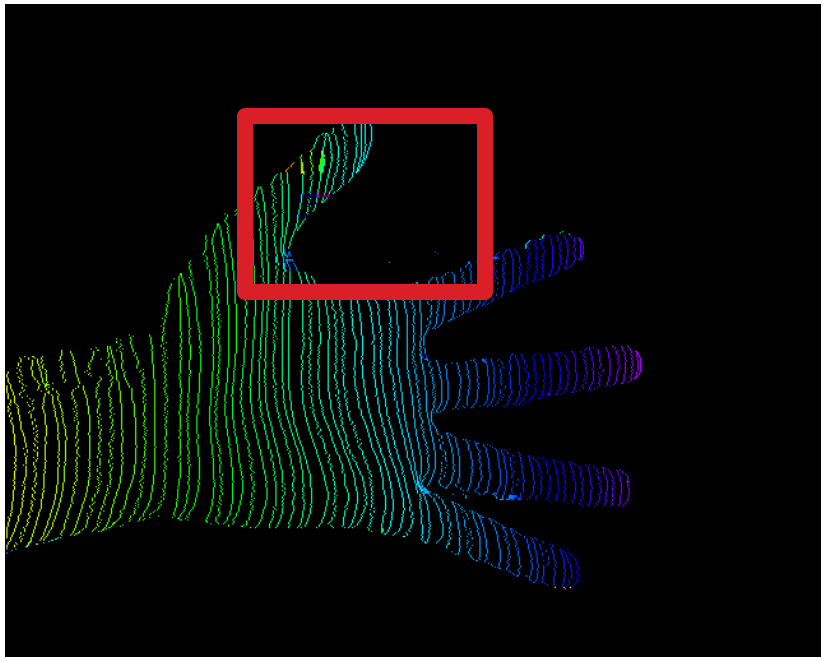


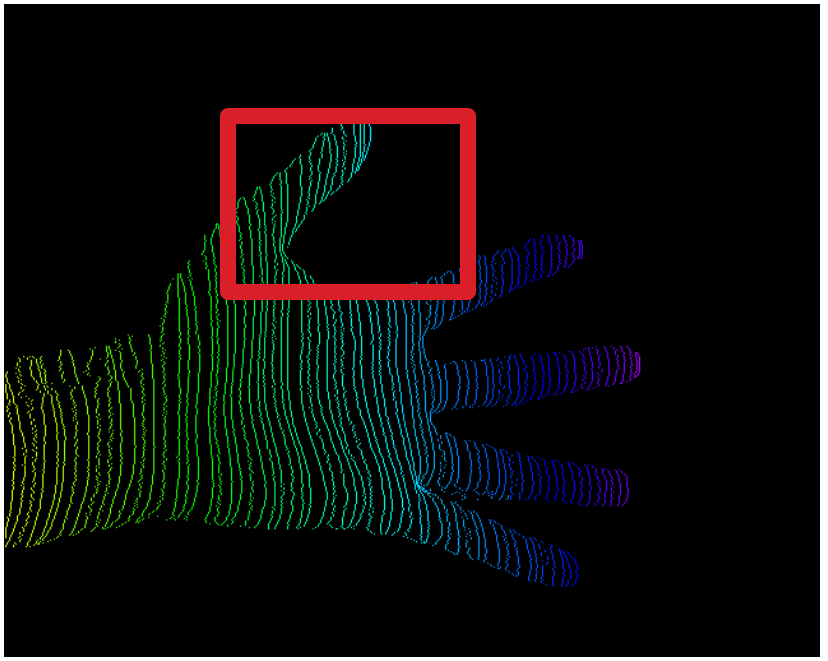
Proposed

Result – Hamming







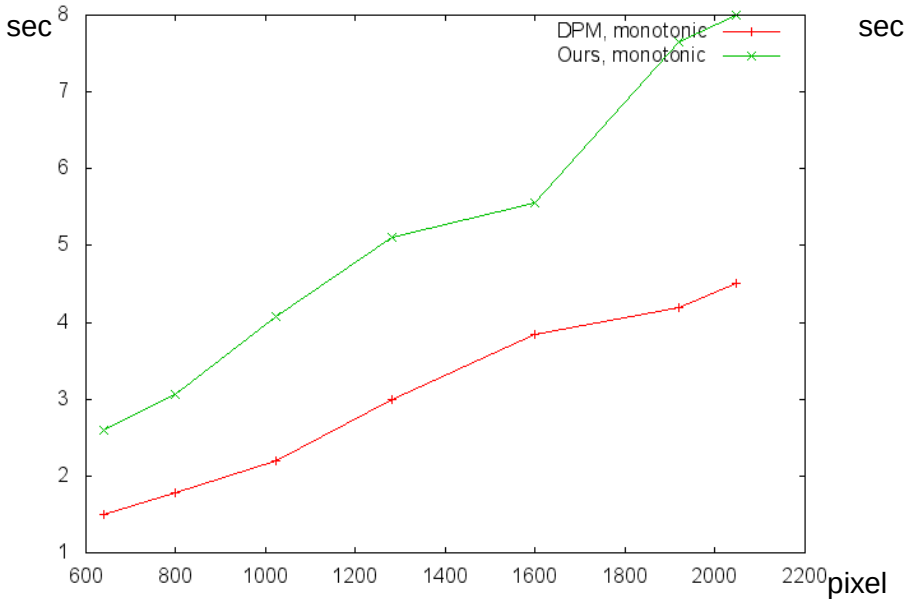


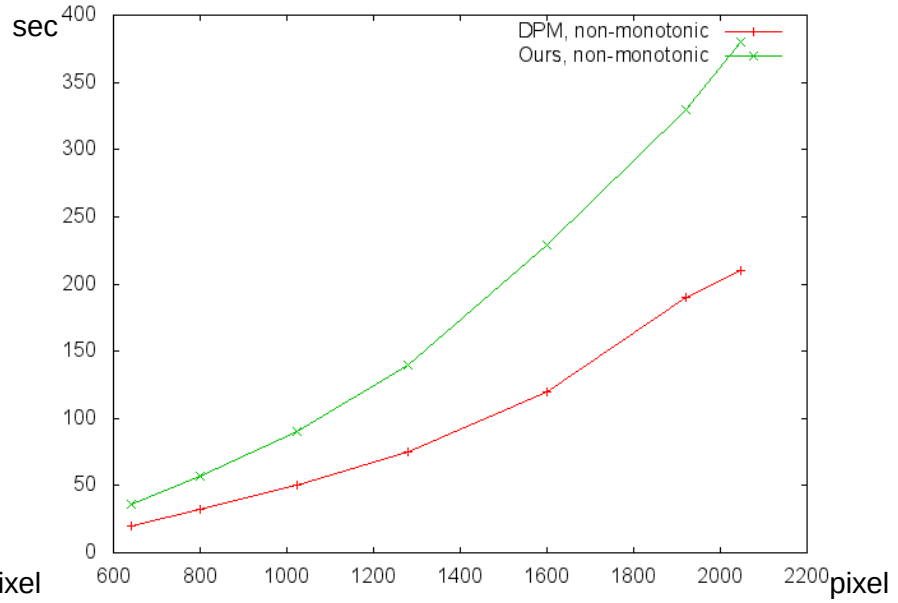
Conventional DPM

Proposed

Timing

- CPU: Intel Core i7 X940 2.13GHz
- Input:
  - Image width : w = 640 ~ 2048
  - Image height : h = 480
  - Code length : m = 110
  - Window uniqueness : n = 4



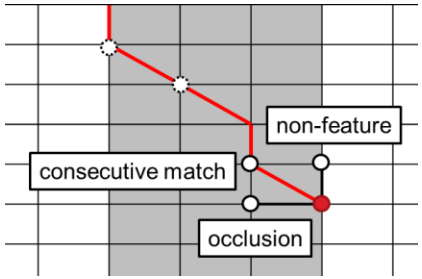


Monotonicity assumption : O(whm)

No monotonicity assumption : $O(w^2hm)$

Discussion

- Significant improvement on depth boundaries.
  - The boundaries are ***always*** unreliable in the conventional DPM.
- 2 ~ 3 time longer computation time
  - Additional data structure is required for the path of consecutive matches.
  - GPU-implementation for real-time reconstruction
- Subtle improvement ?
  - Conventional DPM is tuned for fair comparison.
    - Penalty for pattern break
    - Range of stripe interval
- Streaking artifacts
  - Fundamental limitation of scanline-based algorithm
  - Considering inter-scanline consistency
- Quantitative comparison missing



Conclusion

- Two-level Dynamic Programming Matching
  - Optimal decoding of color stripes
  - Window uniqueness constraint
  - Same complexity as conventional methods : O(whm)
- Applicable to several systems
  - Independent of color stripes
  - Demonstration using 4 different patterns
  - Achieved better results with little additional cost
- Optimal v.s. Sub-optimal
  - Combination with sub-optimal algorithms for inter-scanline consistency
- Practical issues
  - Constant factors matter
  - Efficient implementation required