Interactive Media Systems Group
Software Technology & Interactive Systems
Vienna University of Technology

Laboratoire Central des Ponts et Chaussées

Evaluation of Different Methods for Using Colour Information in Global Stereo Matching Approaches

Michael Bleyer[1], Sylvie Chambon[2], Uta Poppe[1] and Margrit Gelautz[1]

[1]Vienna University of Technology, Austria
[2]Laboratoire Central des Ponts et Chaussées, Nantes, France

Dense Stereo Matching

(Left Image)

(Right Image)

Dense Stereo Matching

(Left Image)

(Right Image)

(Disparity Map)

Structure

- Introduction
- Benchmark design
  - Evaluated energy functions
  - Applied optimization methods
  - Parameter estimation
- Results
- Conclusions

Introduction

- Evaluation of stereo energy functions.
- Two key questions:
  - Does colour help to improve the performance of global stereo methods?
  - What is the best method for using colour? (Colour system, Pixel difference)
- Observation:
  - Colour is expected to reduce matching ambiguities.
  - However, a lot of researchers do not want to use colour information.

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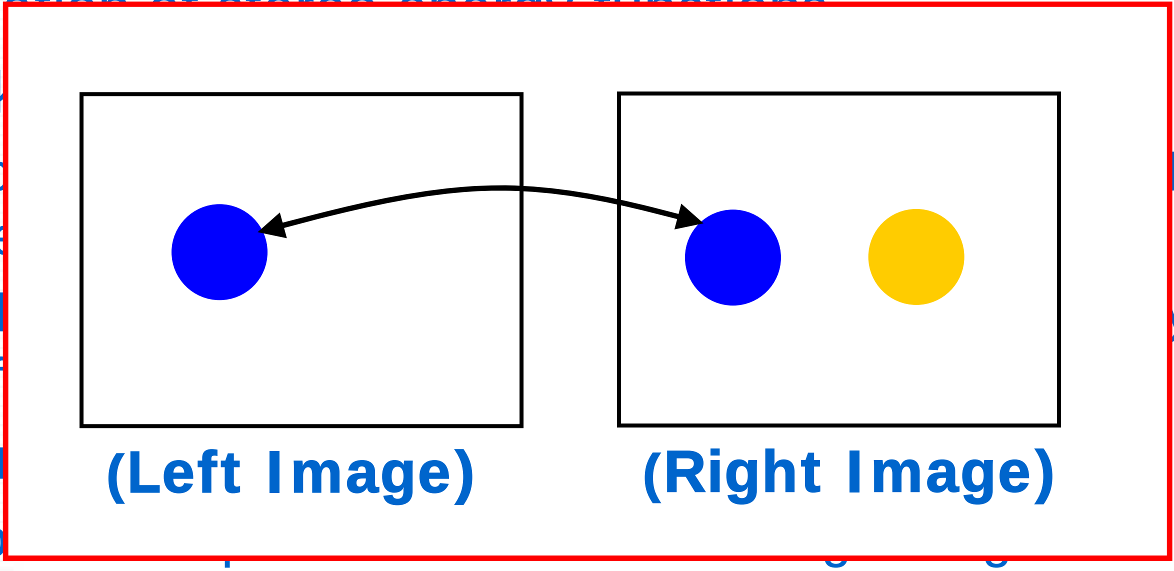

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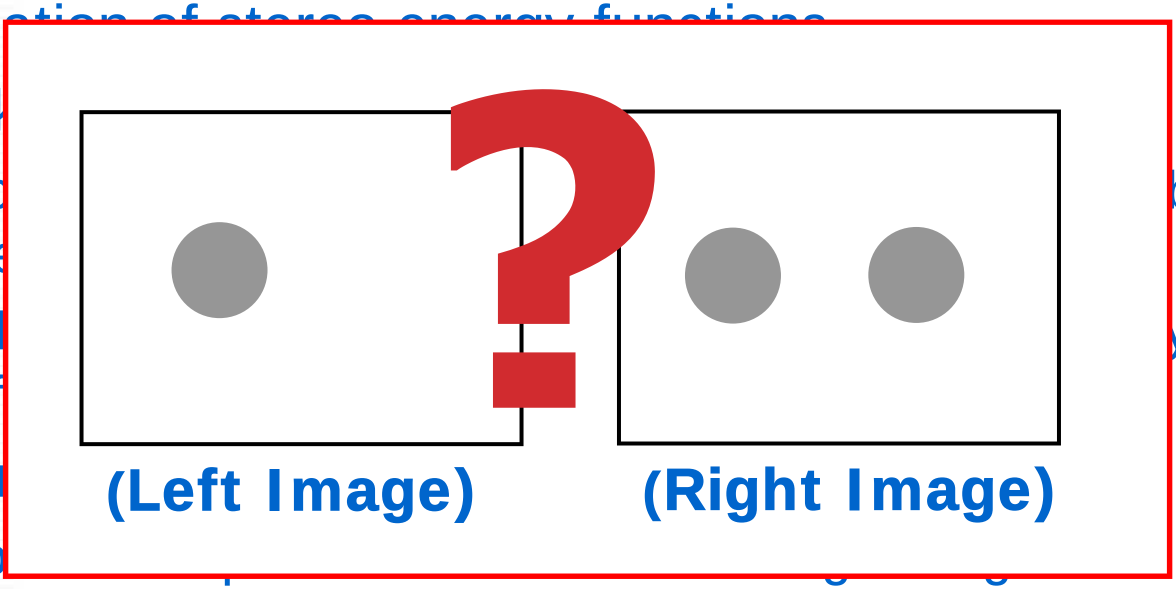

Introduction

- Evaluation of stereo energy functions.
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Energy Functions

$$E(D) = \sum_{p \in \mathcal{I}} m(p, p - d_p) + \sum_{(p,p') \in \mathcal{N}} s(d_p, d_{p'})$$

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- Data term
  - Photo consistency assumption
  - Computes colour difference between corresponding pixels
  - Focus of this study

Energy Functions

$$E(D) = \sum_{p \in \mathcal{I}} m(p, p - d_p) + \sum_{(p,p') \in \mathcal{N}} s(d_p, d_{p'})$$

- Smoothness term
  - Smoothness assumption
  - Penalizes neighbouring pixels assigned to different disparities

Data Term – Colour Spaces

- 10 different choices evaluated:
  - Primary systems:
    - ***RGB, XYZ;***
  - Luminance-chrominance systems:
    - ***LUV, LAB, AC_1C_2, YC_1C_2;***
  - Perceptual systems:
    - ***HSI;***
  - Statistical independent component systems:
    - ***$I_1I_2I_3$, $H_1H_2H_3$;***
  - Use of intensity values only:
    - ***Grey;***

Data Term – Difference Measurements

- 2 choices evaluated:
  - L1 distance (Sum-of-absolute-differences)

$$m^{L_1}(p,q) = \sum_{1 \leq i \leq 3} |p_i - q_i|$$

  - L2 distance (Euclidean distance)

$$m^{L_2}(p,q) = \sqrt{\sum_{1 \leq i \leq 3} (p_i - q_i)^2}$$

- Special treatment for *HSI* and *Grey.*
- In total, 18 different energy functions evaluated in this study.

Smoothness Term

$$E(D) = \sum_{p \in \mathcal{I}} m(p, p - d_p) + \sum_{(p,p') \in \mathcal{N}} s(d_p, d_{p'})$$

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Modified Potts model

Smoothness Term

$$E(D) = \sum_{p \in \mathcal{I}} m(p, p - d_p) + \sum_{(p,p') \in \mathcal{N}} s(d_p, d_{p'})$$

Modified Potts model

$$s(d_p, d_q) = \begin{cases} 0 & : \quad d_p = d_q \\ P_1 & : \quad |d_p - d_q| = 1 \\ P_2 & : \quad \text{otherwise.} \end{cases}$$

Smoothness Term

$$E(D) = \sum_{p \in \mathcal{I}} m(p, p - d_p) + \sum_{(p,p') \in \mathcal{N}} s(d_p, d_{p'})$$

Modified Potts model

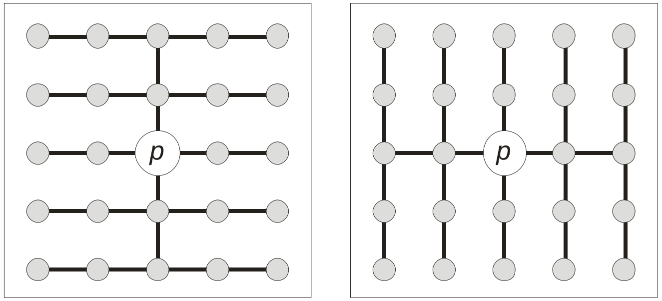
$$s(d_p, d_q) = \begin{cases} 0 & : \quad d_p = d_q \\ P_1 & : \quad |d_p - d_q| = 1 \\ P_2 & : \quad \text{otherwise.} \end{cases}$$

Weighted by intensity gradient

$$P_2 = \begin{cases} P_3 \cdot P_2' & : \quad |I_p - I_q| < T \\ P_2' & : \quad \text{otherwise} \end{cases}$$

Energy Optimization

- Computing energy minimum is known to be NP-hard.
- 2 methods for approximation:
  - Graph-cuts (Alpha-expansion framework):
    - Standard method for energy functions of this type
  - Dynamic programming-based method:
    - Optimizes energy function on a tree structure via DP
    - Two spanning trees generated for each pixel



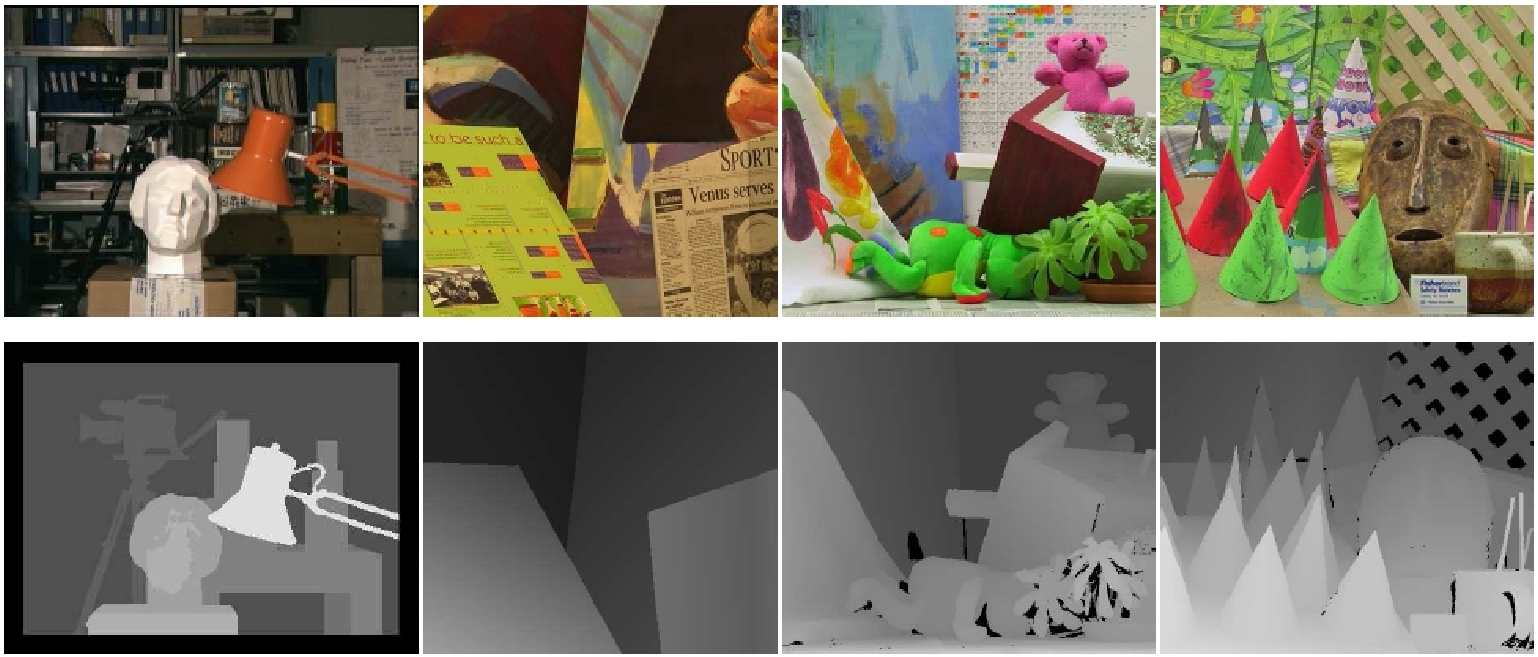
    - Computation time less than a second

Parameter Estimation

- Two important parameters (P_1 and P_2) in the energy function:
  - Balance data and smoothness terms
  - Balance affected by the use of different data terms
  - For fairness, optimize parameter settings for each of the 18 energy functions separately
  - Approximately, 100 combinations of P_1 and P_2 tested

The 2003 Sets

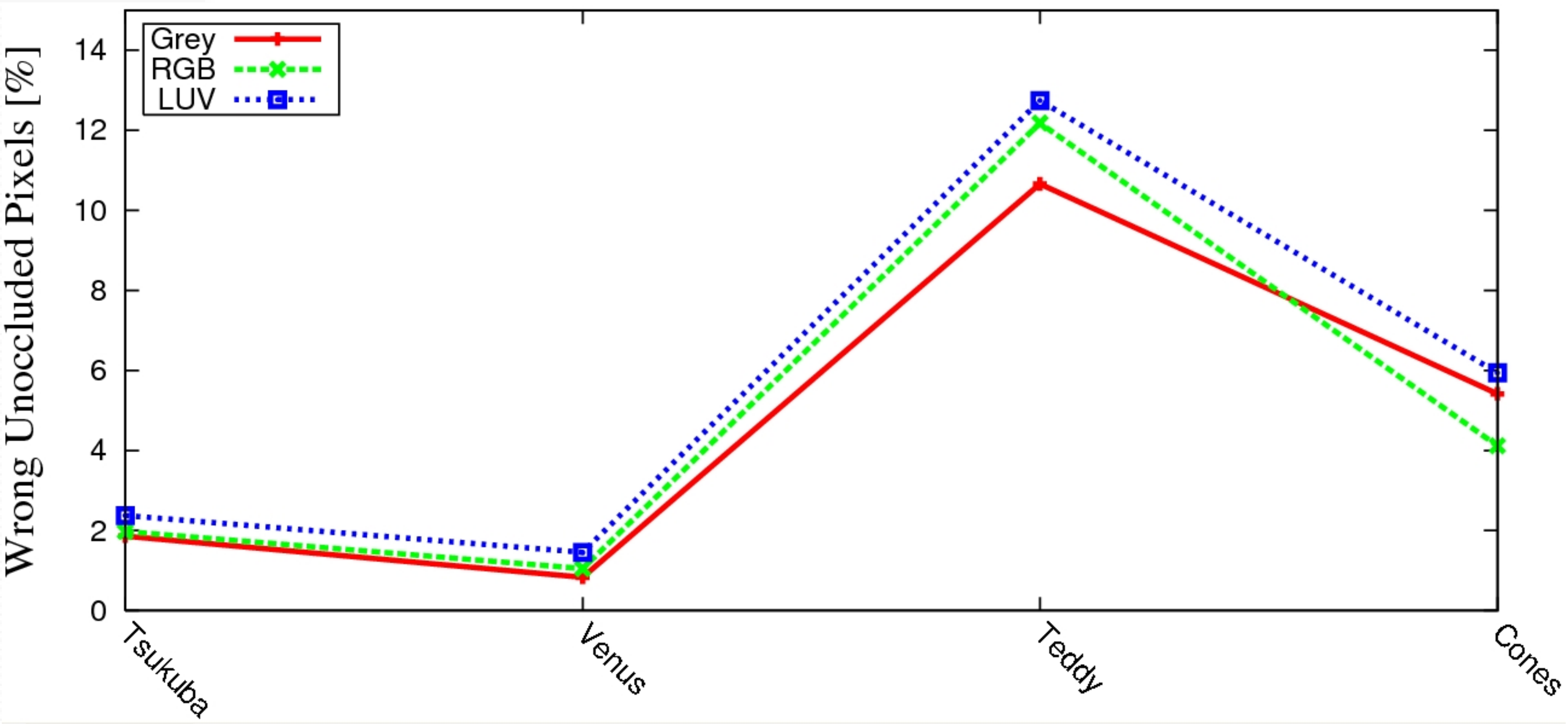
(Left Image)
(Ground Truth)



Tsukuba Venus Teddy Cones

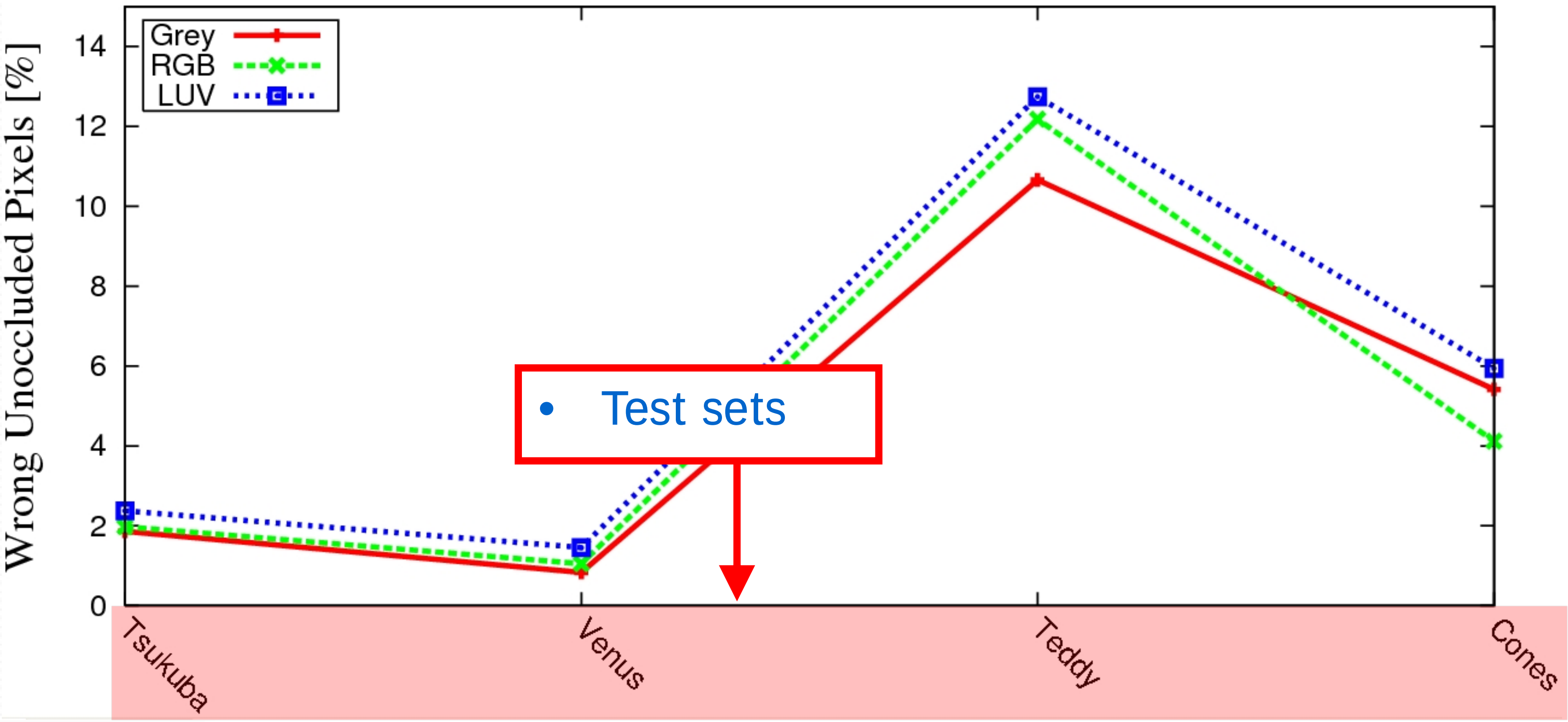
- Currently used in the Middlebury Stereo Vision Benchmark

The 2003 Sets



(Graph-Cut Method - L1 Distance)

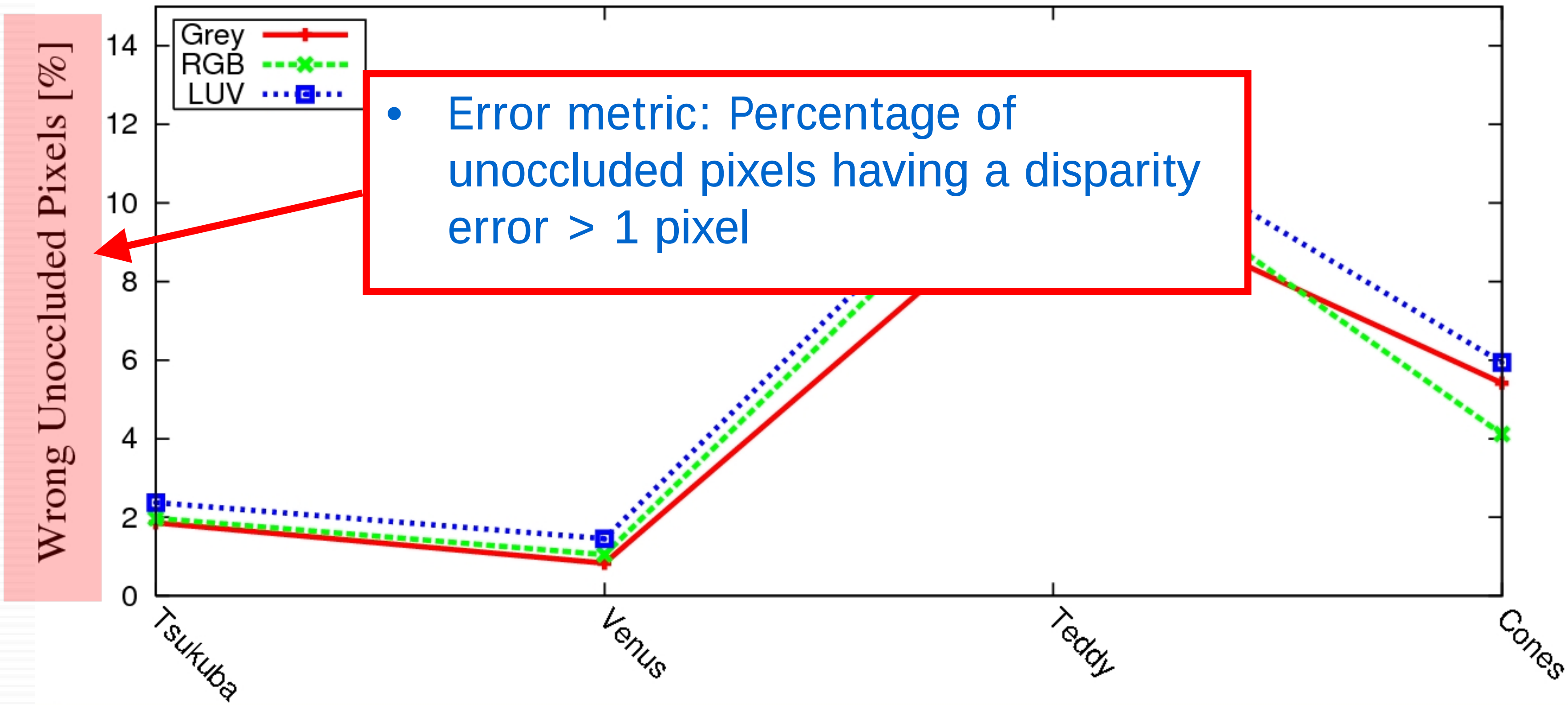
The 2003 Sets



(Graph-Cut Method - L1 Distance)

The 2003 Sets

- Error metric: Percentage of unoccluded pixels having a disparity error > 1 pixel



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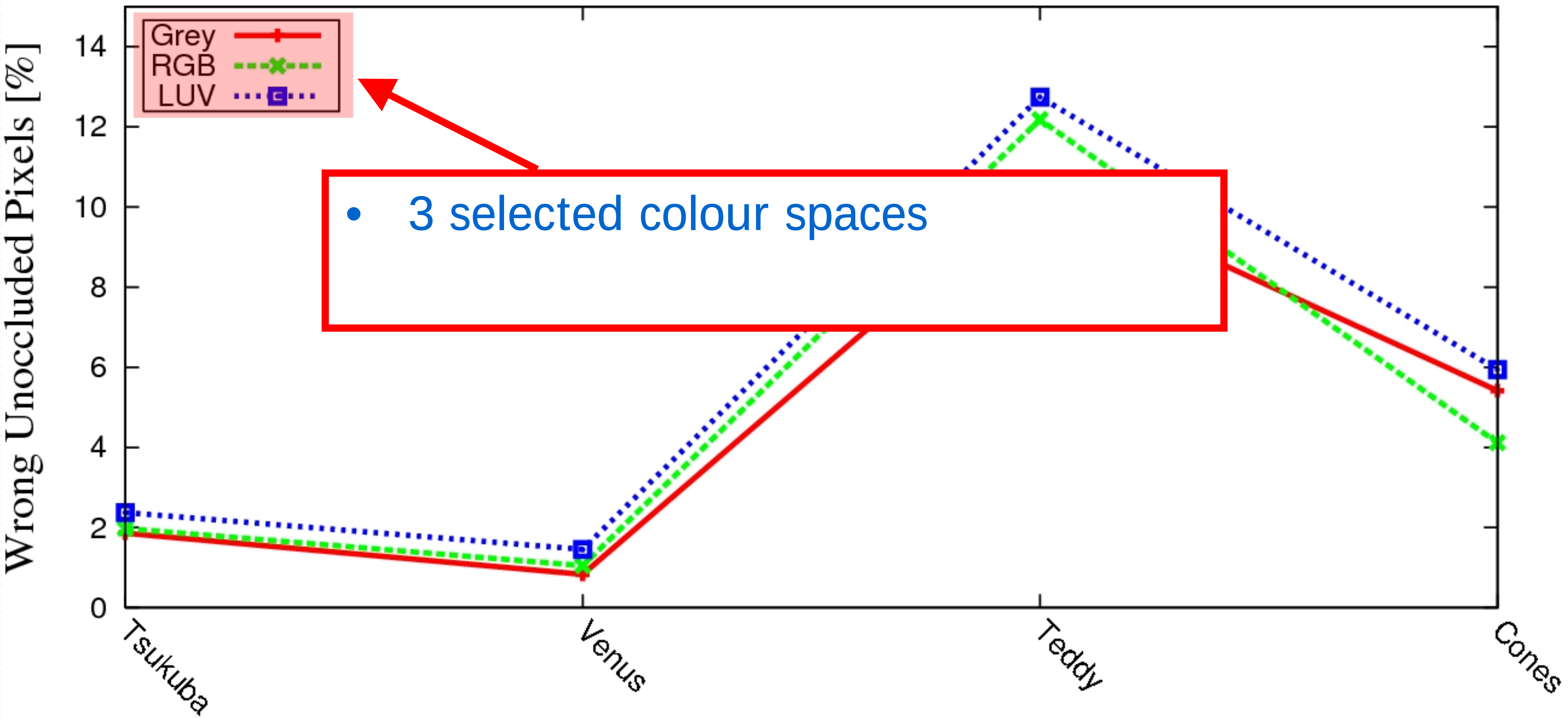
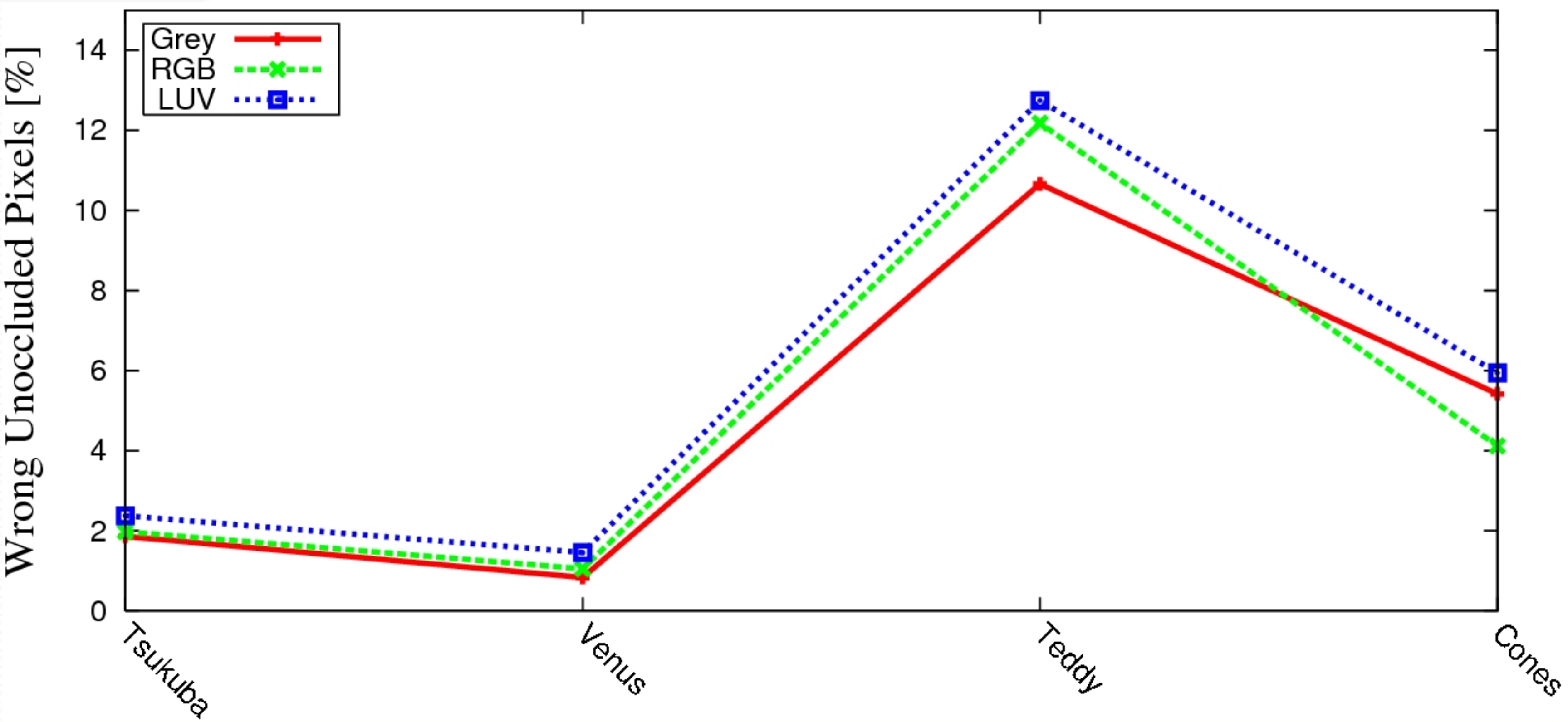


- 3 selected colour spaces

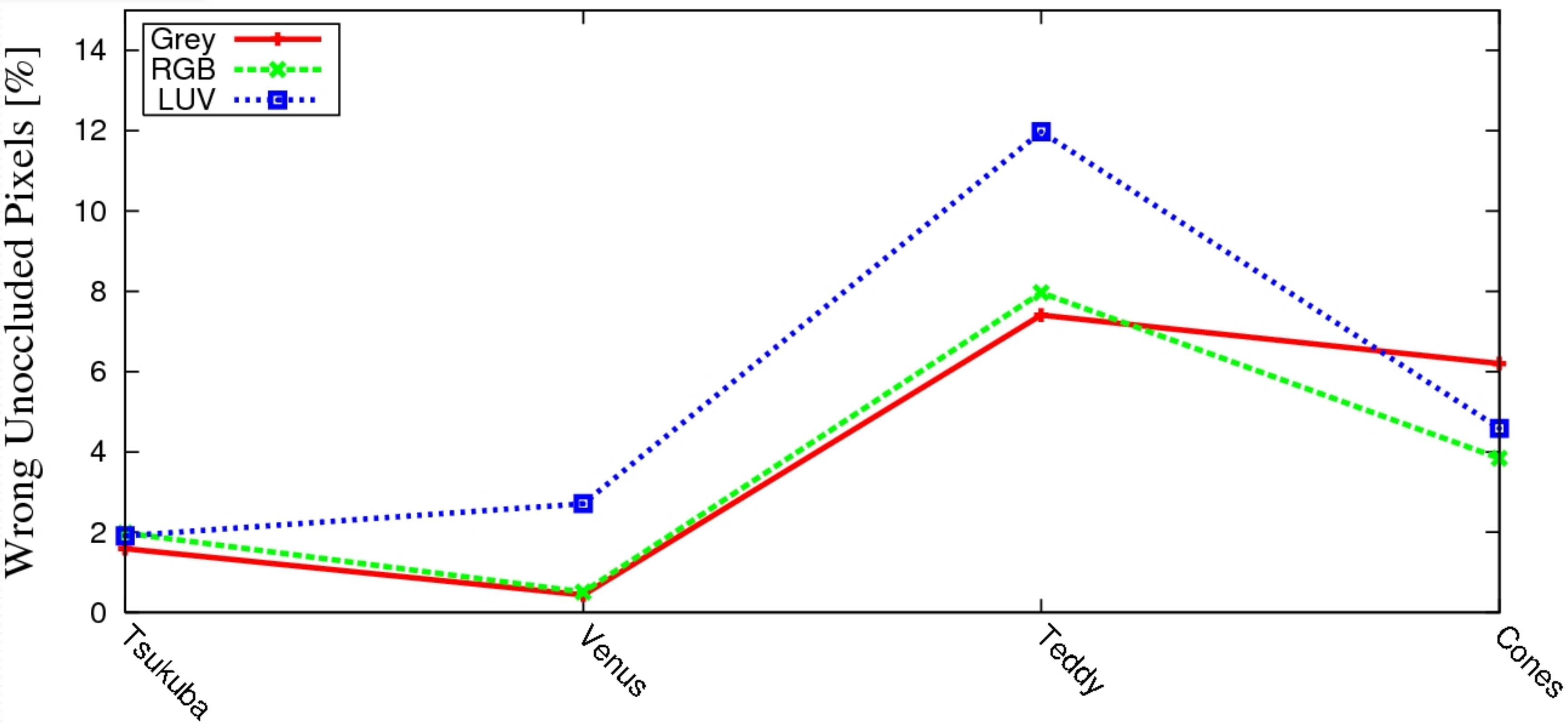
(Graph-Cut Method - L1 Distance)

The 2003 Sets



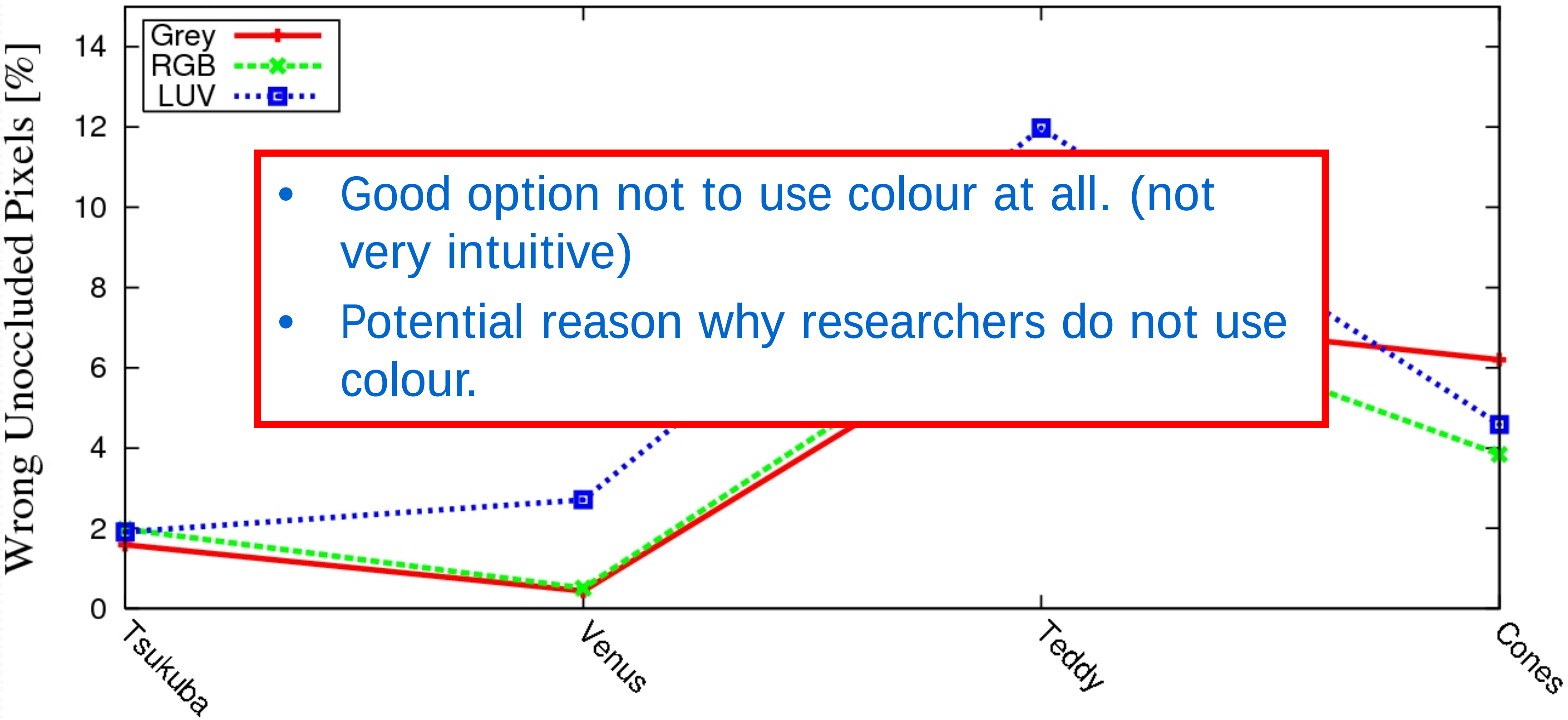
(**Graph-Cut Method - L1 Distance**)

The 2003 Sets



(Dynamic Programming Method - L1 Distance)

The 2003 Sets



- Good option not to use colour at all. (not very intuitive)
- Potential reason why researchers do not use colour.

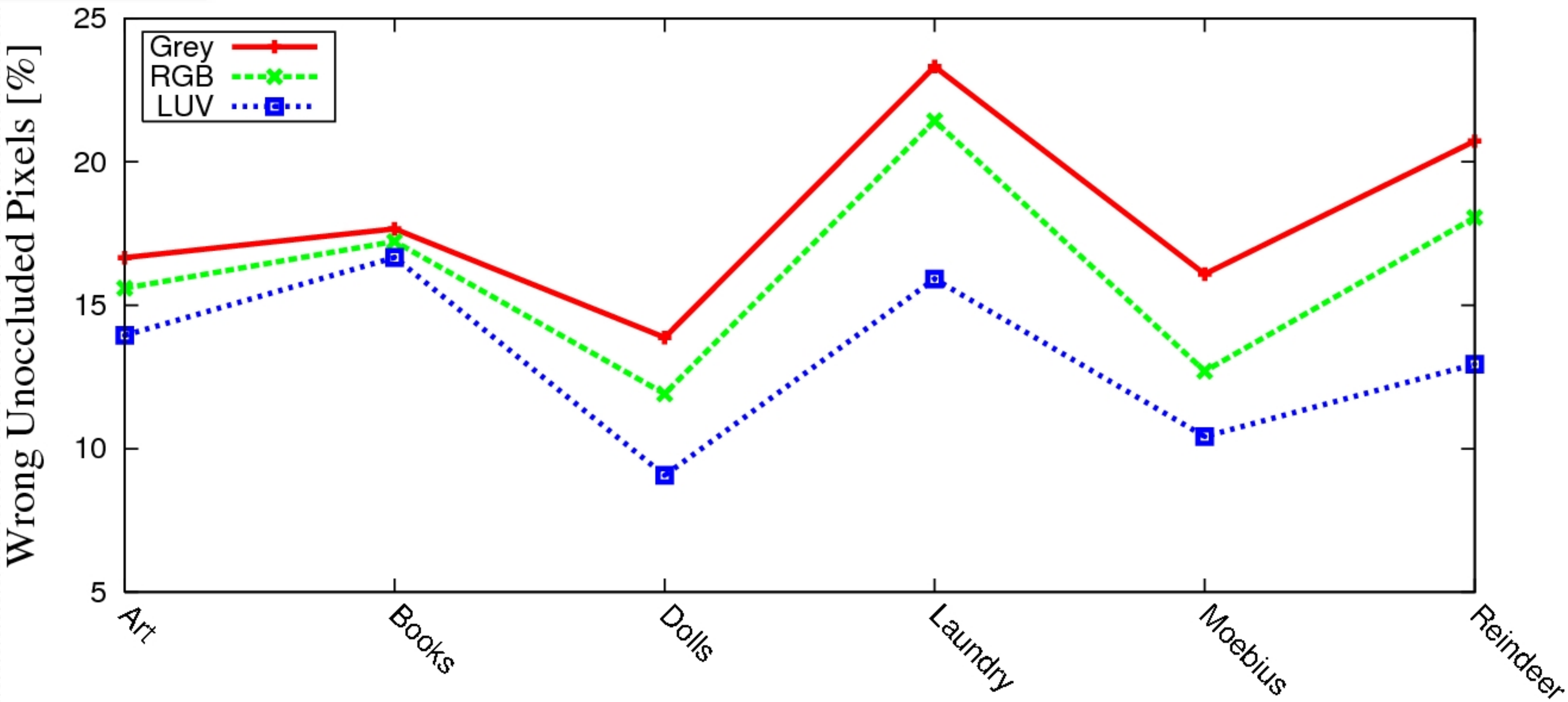
(Dynamic Programming Method - L1 Distance)

The 2005 Sets

Art Books Dolls Laundry Moebius Reindeer

- More complex in terms of geometry, occlusions and untextured regions

The 2005 Sets



(Graph-Cut Method - L1 Distance)

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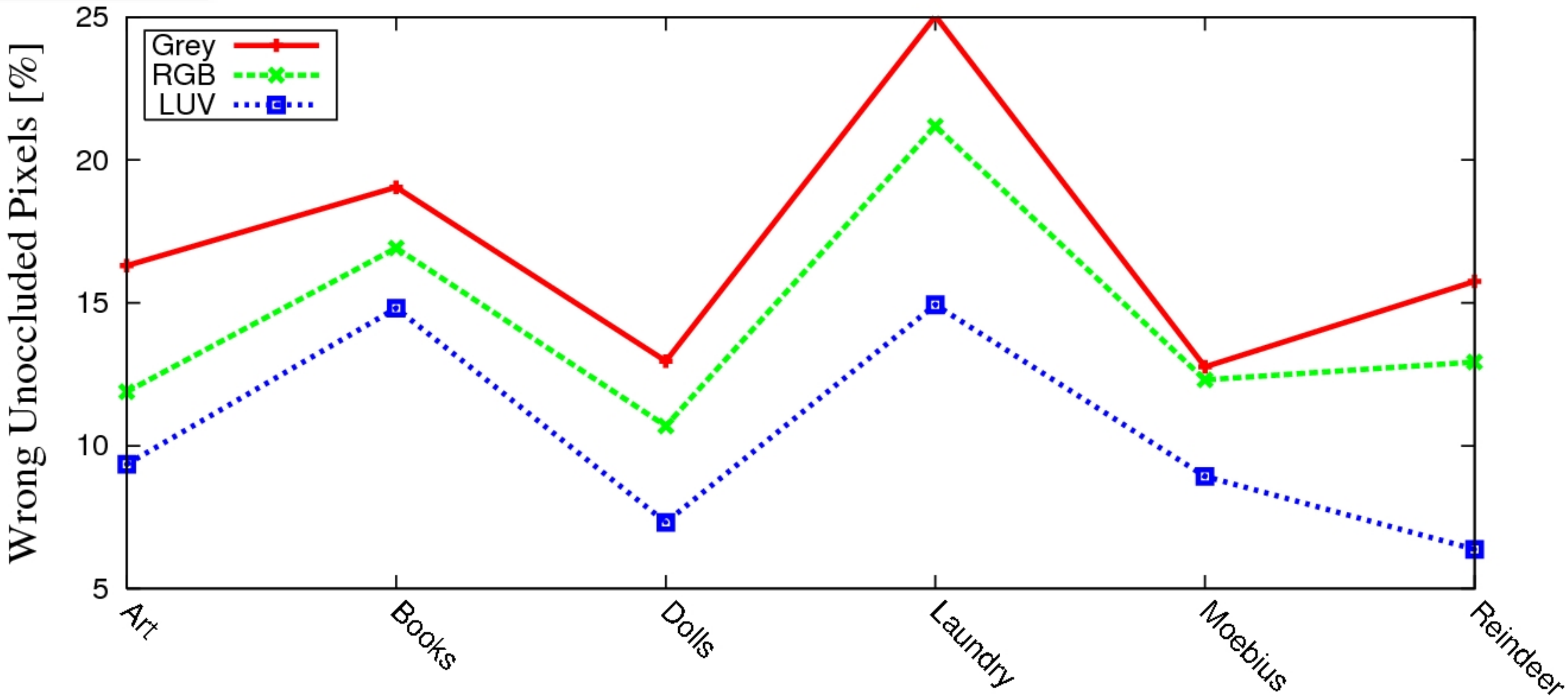
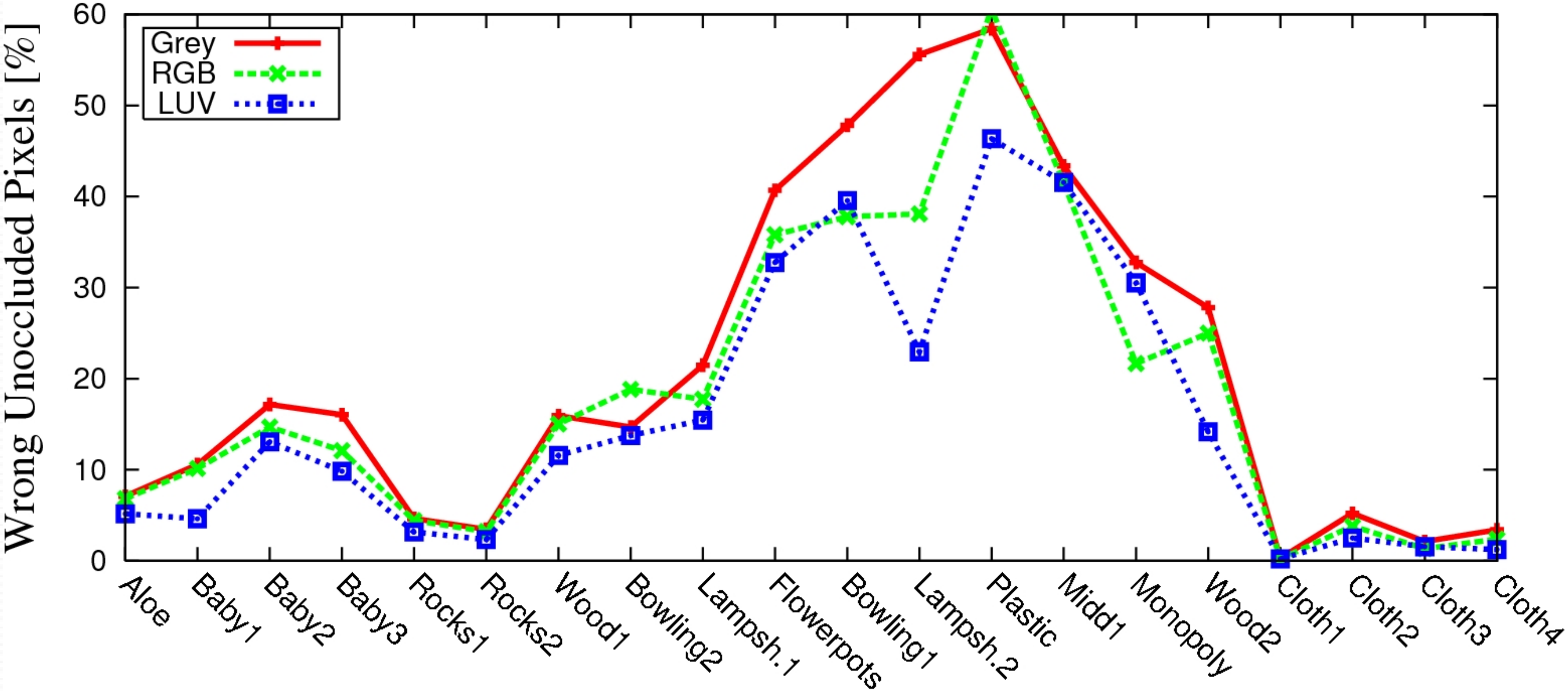


(Dynamic Programming Method - L1 Distance)

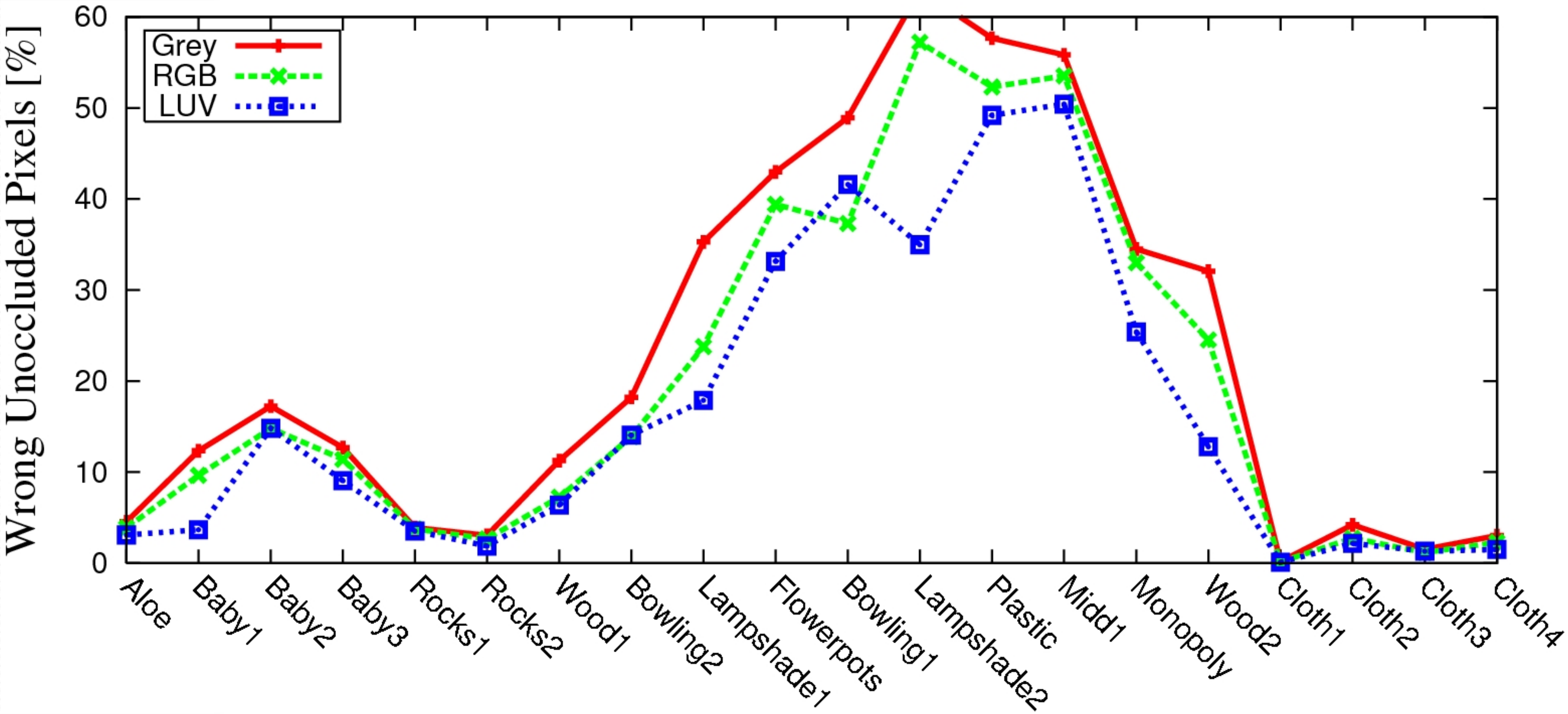
The 2006 Sets

The 2006 Sets



(Graph-Cut Method - L1 Distance)

The 2006 Sets



(Dynamic Programming Method - L1 Distance)

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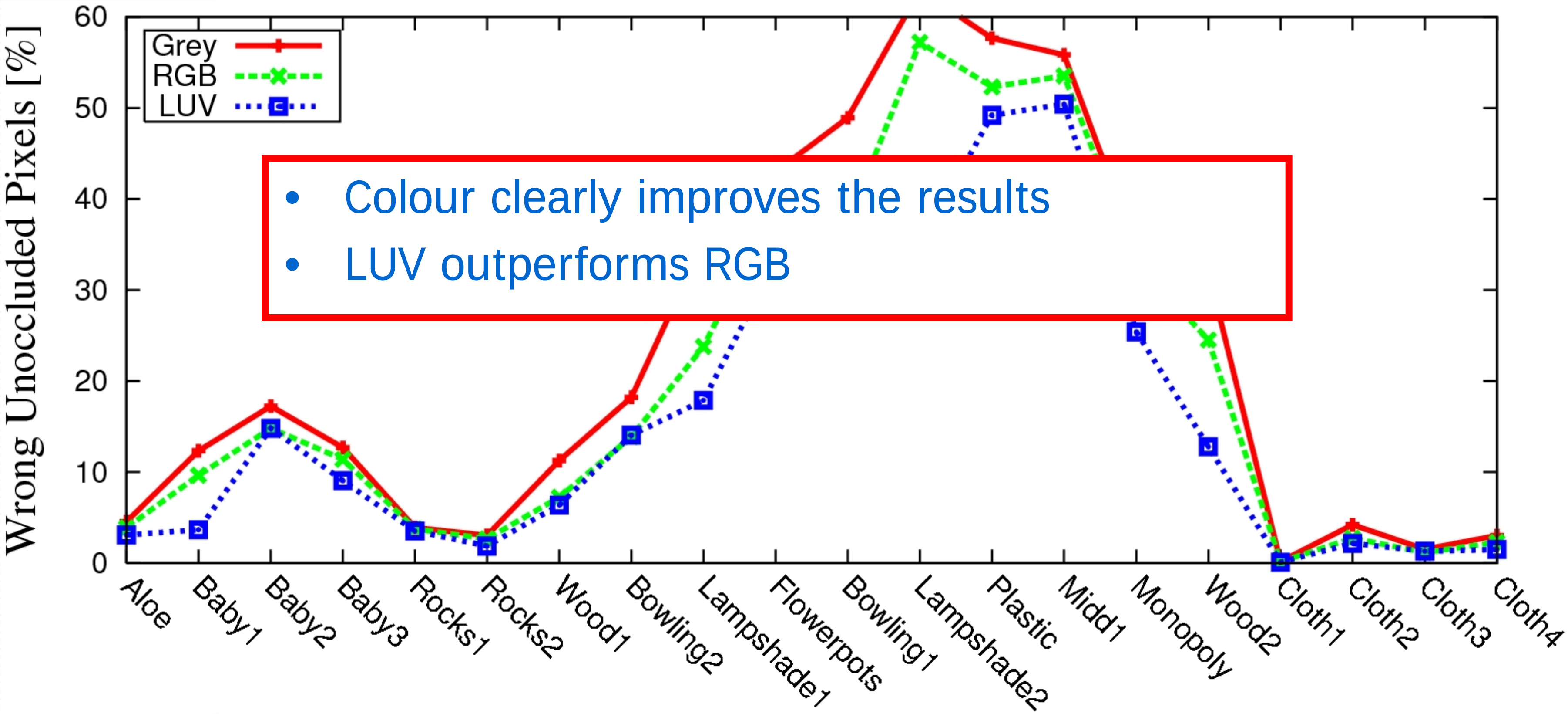

- Colour clearly improves the results
- LUV outperforms RGB

(Dynamic Programming Method - L1 Distance)

Quantitative Results – L1 Distance

Colour Space	All Sets Avg. Rank↓	All Sets Avg. Error
LUV	3.3_1	13.8_1
AC_1C_2	3.3_1	14.6_2
YC_1C_2	3.5_3	15.0_3
$I_1I_2I_3$	4.1_4	15.1_4
RGB	5.5_5	16.2_5
$H_1H_2H_3$	5.7_6	16.8_7
XYZ	6.1_7	16.5_6
LAB	7.2_8	18.4_8
Grey	8.0_9	18.5_{10}
HSI	8.2_{10}	18.4_9

(Graph-Cuts)

Colour Space	All Sets Avg. Rank↓	All Sets Avg. Error
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RGB	4.8_5	16.5_5
XYZ	5.9_6	16.5_6
$H_1H_2H_3$	6.1_7	17.7_7
LAB	7.4_8	18.8_9
HSI	8.0_9	18.2_8
Grey	8.6_{10}	19.3_{10}

(Dynamic Programming)

Quantitative Results – L1 Distance

- Error percentage in unoccluded regions (averaged over all test sets)

Colour Space	All Sets Avg. Rank↓	All Sets Avg. Error
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RGB	5.5_5	16.2_5
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(Graph-Cuts)

- Relative rank in comparison against competing colour systems (averaged over all test sets)
- Table sorted according to this error measurement

$I_1I_2I_3$	4.7_4	15.3_4
RGB	4.8_5	16.5_5
XYZ	5.9_6	16.5_6
$H_1H_2H_3$	6.1_7	17.7_7
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(Dynamic Programming)

Quantitative Results – L1 Distance

(Graph-Cuts)

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$I_1I_2I_3$	4.1_4	15.1_4
RGB	5.5_5	16.2_5
$H_1H_2H_3$	[illegible]	[illegible]
XYZ	[illegible]	[illegible]
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[illegible]	[illegible]	[illegible]
LAB	7.4_8	18.8_9
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Grey	8.6_{10}	19.3_{10}

- Luminance-chrominance systems

Quantitative Results – L1 Distance

Colour Space	All Sets Avg. Rank↓	All Sets Avg. Error
LUV	3.3$_1$	13.8$_1$
AC_1C_2	3.3$_1$	14.6$_2$
YC_1C_2	3.5$_3$	15.0$_3$
$I_1I_2I_3$	4.1$_4$	15.1$_4$
RGB	5.5$_5$	16.2$_5$
$H_1H_2H_3$	5.7$_6$	16.8$_7$
XYZ	6.1$_7$	16.5$_6$
LAB	7.2$_8$	18.4$_8$
Grey	8.0$_9$	18.5$_{10}$
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(Graph-Cuts)

- $I_1I_2I_3$

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AC_1C_2	3.4$_2$	14.8$_3$
YC_1C_2	3.4$_2$	14.7$_2$
$I_1I_2I_3$	4.7$_4$	15.3$_4$
RGB	4.8$_5$	16.5$_5$
XYZ	5.9$_6$	16.5$_6$
$H_1H_2H_3$	6.1$_7$	17.7$_7$
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XYZ	5.9_6	16.5_6
$H_1H_2H_3$	6.1_7	17.7_7
LAB	7.4_8	18.8_9
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(Dynamic Programming)

- RGB

Quantitative Results – L1 Distance

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RGB	5.5_5	[illegible]
$H_1H_2H_3$	5.7_6	16.8_7
XYZ	6.1_7	16.5_6
LAB	7.2_8	18.4_8
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(Graph-Cuts)

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HSI	8.0_9	18.2_8
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(Dynamic Programming)

- $H_1H_2H_3$, XYZ, LAB

Quantitative Results – L1 Distance

Colour Space	All Sets Avg. Rank↓	All Sets Avg. Error
LUV	3.3_1	13.8_1
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$H_1H_2H_3$	5.7_6	16.8_7
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LAB	7.2_8	18.4_8
Grey	8.0_9	18.5_{10}
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(Graph-Cuts)

- Grey

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YC_1C_2	3.4_2	14.7_2
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(Dynamic Programming)

Quantitative Results – L1 Distance

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YC_1C_2	3.5_{3}	15.0_{3}
$I_1I_2I_3$	4.1_{4}	15.1_{4}
RGB	5.5_{5}	16.2_{5}
$H_1H_2H_3$	5.7_{6}	16.8_{7}
XYZ	6.1_{7}	16.5_{6}
LAB	7.2_{8}	18.4_{8}
Grey	8.0_{9}	18.5_{10}
HSI	8.2_{10}	18.4_{9}

(Graph-Cuts)

- HSI

Colour Space	All Sets Avg. Rank↓	All Sets Avg. Error
LUV	2.8_{1}	13.7_{1}
AC_1C_2	3.4_{2}	14.8_{3}
YC_1C_2	3.4_{2}	14.7_{2}
$I_1I_2I_3$	4.7_{4}	15.3_{4}
RGB	4.8_{5}	16.5_{5}
XYZ	5.9_{6}	16.5_{6}
$H_1H_2H_3$	6.1_{7}	17.7_{7}
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(Dynamic Programming)

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[illegible]	[illegible]	$[illegible]5.[illegible]_3$
[illegible]	[illegible]	$[illegible]5.[illegible]_4$
[illegible]	[illegible]	$[illegible]6.[illegible]_5$
$H_1H_2H_3$	5.7_6	$16.[illegible]_7$
XYZ	6.1_7	$16.[illegible]_6$
LAB	7.2_8	$18.[illegible]_8$
Grey	8.0_9	18.5_{10}
HSI	8.2_{10}	18.4_9

- 25.4% less errors

(Graph-Cuts)

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LUV	2.8_1	13.7_1
AC_1C_2	3.4_2	$14[illegible]8_3$
[illegible]	[illegible]	$[illegible]4[illegible]7_2$
[illegible]	[illegible]	$[illegible]5[illegible]3_4$
[illegible]	[illegible]	$[illegible]6[illegible]5_5$
XYZ	5.9_6	$16[illegible]5_6$
$H_1H_2H_3$	6.1_7	$17[illegible]7_7$
LAB	7.4_8	$18[illegible]8_9$
HSI	8.0_9	$18[illegible]2_8$
Grey	8.6_{10}	19.3_{10}

- 29.0% less errors

(Dynamic Programming)

Quantitative Results – L1 Distance

Colour Space	All Sets: Avg. Rank↓	All Sets: Avg. Error
LUV	3.3_1	13.8_1
[illegible]	[illegible]	$14.[illegible]_2$
[illegible]	[illegible]	$15.[illegible]_3$
[illegible]	[illegible]	$15.[illegible]_4$
RGB	5.5_5	16.2_5
$H_1H_2H_3$	5.7_6	16.8_7
XYZ	6.1_7	16.5_6
LAB	7.2_8	18.4_8
Grey	8.0_9	18.5_{10}
HSI	8.2_{10}	18.4_9

- 14.8% less errors

(Graph-Cuts)

Colour Space	All Sets: Avg. Rank↓	All Sets: Avg. Error
LUV	2.8_1	13.7_1
[illegible]	[illegible]	14.8_3
[illegible]	[illegible]	14.7_2
[illegible]	[illegible]	15.3_4
RGB	4.8_5	16.5_5
XYZ	5.9_6	16.5_6
$H_1H_2H_3$	6.1_7	17.7_7
LAB	7.4_8	18.8_9
HSI	8.0_9	18.2_8
Grey	8.6_{10}	19.3_{10}

- 17.0% less errors

(Dynamic Programming)

Quantitative Results – L1 Distance

Colour Space	All Sets Avg. Rank↓	All Sets Avg. Error
LUV	3.3_1	13.8_1
AC_1C_2	3.3_1	14.6_2
YC_1C_2	3.5_3	15.0_3
$I_1I_2I_3$	4.1_4	15.1_4
RGB	5.5_5	16.2_5
$H_1H_2H_3$	5.7_6	16.8_7
XYZ	6.1_7	16.5_6
LAB	7.2_8	18.4_8
Grey	8.0_9	18.5_{10}
HSI	8.2_{10}	18.4_9

(Graph-Cuts)

- 0.7% less errors for DP

Colour Space	All Sets [illegible]	All Sets …vg. …ror
LUV	2.8[illegible]	13.7_1
AC_1C_2	3.4_2	14.8_3
YC_1C_2	3.4_2	14.7_2
$I_1I_2I_3$	4.7_4	15.3_4
RGB	4.8_5	16.5_5
XYZ	5.9_6	16.5_6
$H_1H_2H_3$	6.1_7	17.7_7
LAB	7.4_8	18.8_9
HSI	8.0_9	18.2_8
Grey	8.6_{10}	19.3_{10}

(Dynamic Programming)

Quantitative Results – L1 Distance

Colour Space	All Sets Avg. Rank↓	All Sets Avg. Error
LUV	3.3_{1}	13.8_{1}
AC_1C_2	3.3_{1}	14.6_{2}
YC_1C_2	[illegible]	[illegible]
$I_1I_2I_3$	[illegible]	[illegible]
RGB	[illegible]	[illegible]
$H_1H_2H_3$	[illegible]	[illegible]
XYZ	[illegible]	[illegible]
LAB	[illegible]	[illegible]
Grey	8.0_{9}	18.5_{10}
HSI	8.2_{10}	18.4_{9}

(Graph-Cuts)

Colour Space	All Sets Avg. Rank↓	All Sets Avg. Error
LUV	[illegible]	13.7_{1}
AC_1C_2	3.4_{2}	14.8_{3}
[illegible]	[illegible]	14.7_{2}
[illegible]	[illegible]	15.3_{4}
[illegible]	[illegible]	16.5_{5}
[illegible]	[illegible]	16.5_{6}
[illegible]	[illegible]	17.7_{7}
LAB	[illegible]	18.8_{9}
HSI	8.0_{9}	18.2_{8}
Grey	8.6_{10}	19.3_{10}

(Dynamic Programming)

- 0.7% less errors for DP

- There seems to lie more potential in the energy modelling component than in energy optimization.

Quantitative Results – L1 vs L2

Colour Space	All Sets Avg. Rank↓	All Sets Avg. Error
LUV	3.3_1	13.8_1
AC_1C_2	3.3_1	14.6_2
YC_1C_2	3.5_3	15.0_3
$I_1I_2I_3$	4.1_4	15.1_4
RGB	5.5_5	16.2_5
$H_1H_2H_3$	5.7_6	16.8_7
XYZ	6.1_7	16.5_6
LAB	7.2_8	18.4_8
Grey	8.0_9	18.5_{10}
HSI	8.2_{10}	18.4_9

(Graph-Cuts – L1)

Colour Space	All Sets Avg. Rank↓	All Sets Avg. Error
LUV	3.2_1	14.5_1
YC_1C_2	3.8_2	15.6_3
AC_1C_2	4.0_3	15.5_2
$I_1I_2I_3$	4.8_4	16.2_5
RGB	5.1_5	16.7_6
XYZ	5.4_6	16.0_4
$H_1H_2H_3$	6.6_7	17.9_7
LAB	6.8_8	18.3_9
Grey	7.6_9	18.5_{10}
HSI	7.7_{10}	17.9_8

(Graph-Cuts – L2)

Quantitative Results – L1 vs L2

Colour Space	All Sets Avg. Rank↓	All Sets Avg. Error
LUV	3.3_1	13.8_1
AC_1C_2	3.3_1	14.6_2
YC_1C_2	[illegible]	[illegible]
$I_1I_2I_3$	[illegible]	[illegible]
RGB	[illegible]	[illegible]
$H_1H_2H_3$	[illegible]	[illegible]
XYZ	[illegible]	[illegible]
LAB	[illegible]	[illegible]
Grey	8.0_9	18.5_{10}
HSI	8.2_{10}	18.4_9

(Graph-Cuts – L1)

Colour Space	All Sets Avg. Rank↓	All Sets Avg. Error
LUV	[illegible]	14.5_1
YC_1C_2	3.8_2	15.6_3
[illegible]	[illegible]	15.5_2
[illegible]	[illegible]	16.2_5
[illegible]	[illegible]	16.7_6
[illegible]	[illegible]	16.0_4
[illegible]	[illegible]	17.9_7
[illegible]	[illegible]	18.3_9
Grey	7.6_9	18.5_{10}
HSI	7.7_{10}	17.9_8

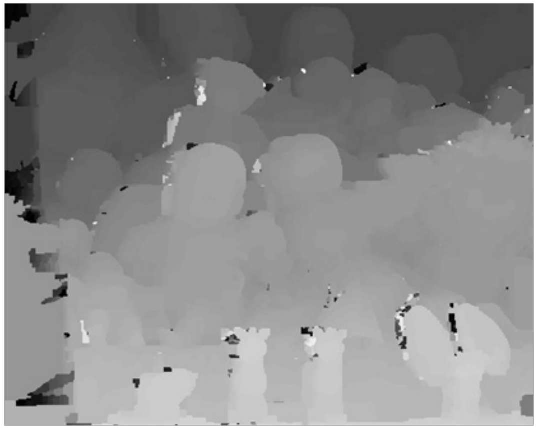
(Graph-Cuts – L2)

- 4.8% less errors for L1

- The choice of the colour system seems to be more important than the difference method.

Example: Dolls Test Set – Graph-Cuts





(Left Image) **(Grey - Disparity)** **(LUV - Disparity)**

Example: Dolls Test Set – Graph-Cuts

(Left Image)

(Grey - Errors)

(LUV - Errors)

Example: Dolls Test Set – Graph-Cuts

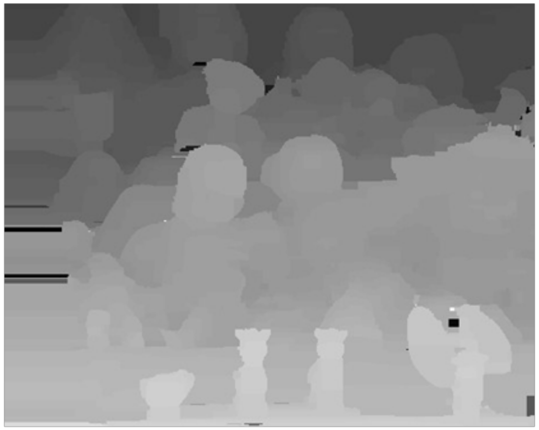
(Left Image)

(Grey - Errors)

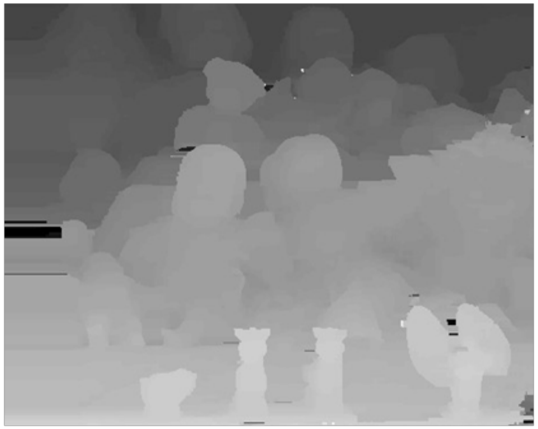
(LUV - Errors)

Example: Dolls Test Set – Dynamic Programming

(Left Image)



(Grey - Disparity)

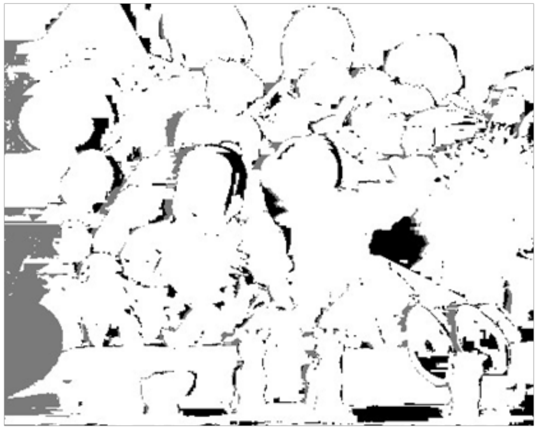


(LUV - Disparity)

Example: Dolls Test Set – Dynamic Programming

(Left Image)

(Grey - Errors)

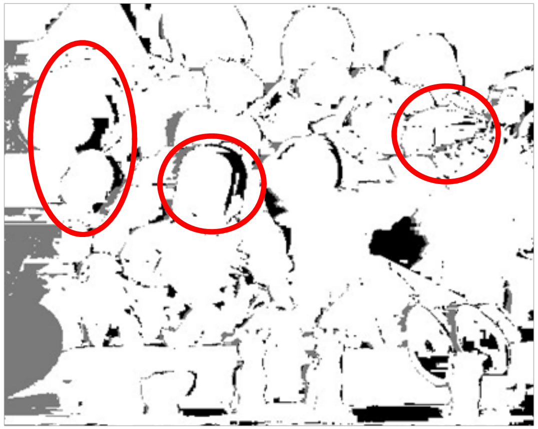


(LUV - Errors)

Example: Dolls Test Set – Dynamic Programming

(Left Image)

(Grey - Errors)



(LUV - Errors)

Conclusions (1)

- Investigation of the role of colour in global stereo methods
- 18 energy functions tested with 2 optimization algorithms on 30 ground truth images
- Colour does not always improve results. (Current Middlebury evaluation set)
- Performance improvement of 25% achieved by using the best-performing colour system instead of grey-scale matching

Conclusions (2)

- Luminance-chrominance systems have shown the best results. (relationship to human perception)
- RGB only gives average results. (most popular colour system)
- Choice of colour system is probably more important than difference method or optimization. (It is worth paying more attention to data term.)

The End

Thank You