Global Optimization Methods for Computer Vision

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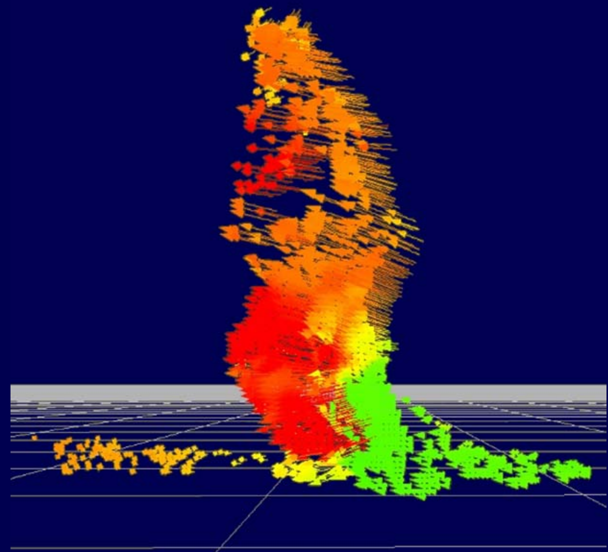
Bonn Vision Workshop, October 8, 2009

Overview

3D reconstruction



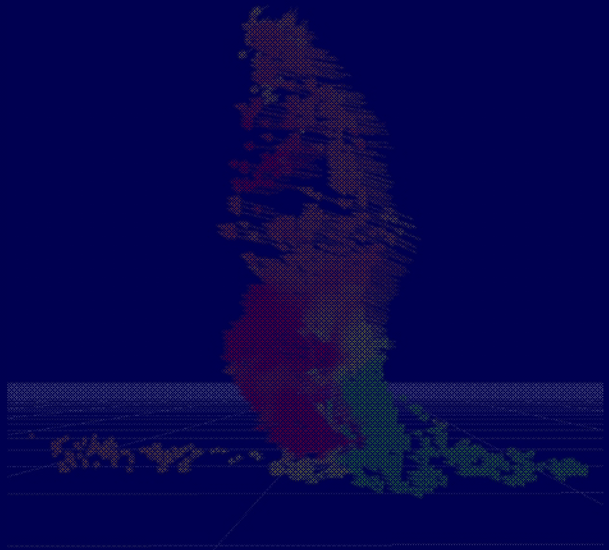
Motion analysis

Shape analysis

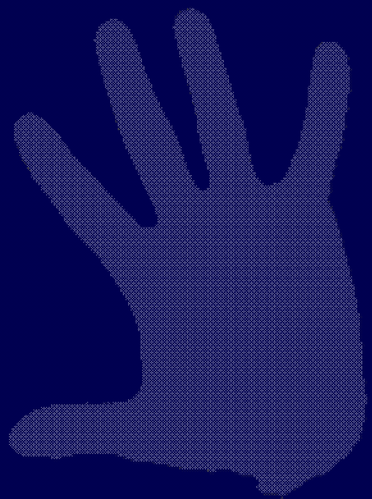
Segmentation & tracking

Overview

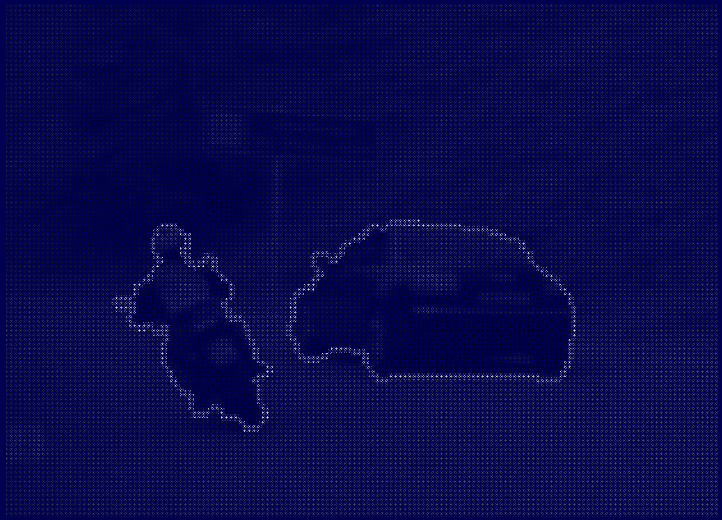
3D reconstruction



Motion analysis



Shape analysis



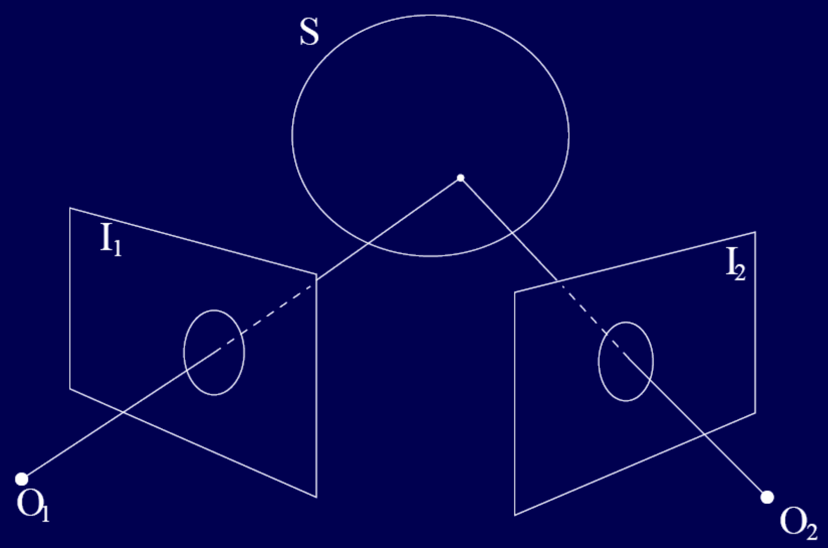
Segmentation & tracking

Multiple View Reconstruction

Multiple View Reconstruction

Photoconsistency function:

$$\rho : \mathbb{R}^3 \to [0, 1]$$



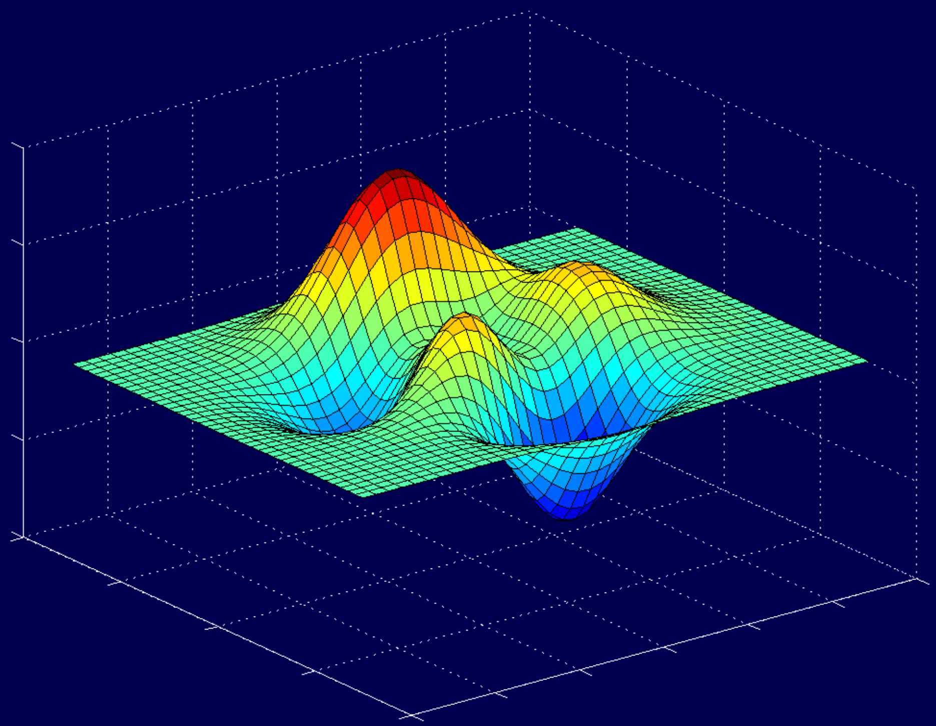
Determine a surface S of optimal photoconsistency by minimizing

$$E(S) = \int_S \rho \, dA$$

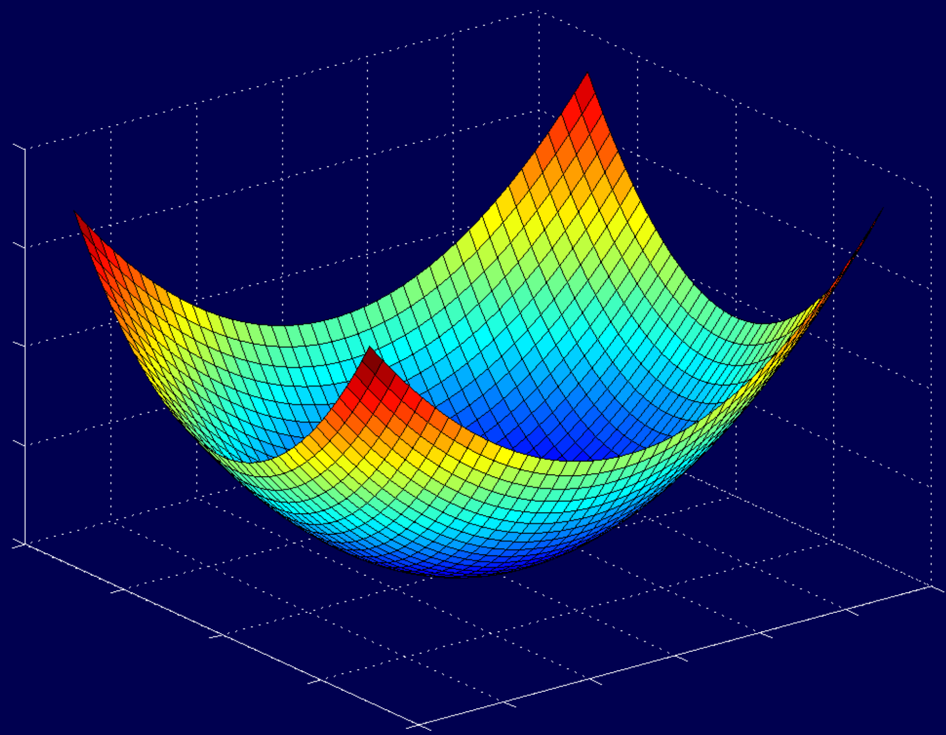
Kolev, Klodt, Brox, Cremers, Int. J. of Computer Vision '09:

Theorem: Globally optimal surfaces can be computed via convex relaxation.

Non-convex versus Convex Energies



Non-convex energy



Convex energy

Middlebury Benchmark

vision.middlebury.edu/mview/eval – Mozilla Firefox

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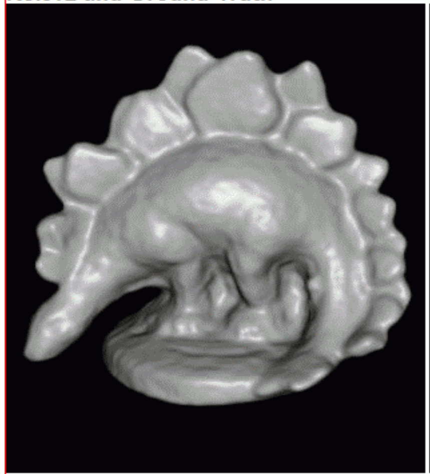
http://vision.middlebury.edu/mview/eval/

Sort By	Temple Full 312 views Acc [mm]	Comp [%]	Temple Ring 47 views Acc [mm]	Comp [%]	Temple Sparse 16 views Acc [mm]	Comp [%]	Dino Full 363 views Acc [mm]	Comp [%]	Dino Ring 48 views Acc [mm]	Comp [%]	Dino Sparse 16 views Acc [mm]	Comp [%]
Furukawa 3	0.49	99.6	0.47	99.6	0.63	99.3	0.33	99.8	0.28	99.8	0.37	99.2
Furukawa 2	0.54	99.3	0.55	99.1	0.62	99.2	0.32	99.9	0.33	99.6	0.42	99.2
Kolev2			0.72	97.8	1.04	91.8			0.43	99.4	0.53	98.3
Zach2	0.51	98.8	0.56	99.0			0.55	98.7	0.51	99.1		
Pons			0.6	99.5	0.9	95.4			0.55	99.0	0.71	97.7
Furukawa	0.65	98.7	0.58	98.5	0.82	94.3	0.52	99.2	0.42	98.8	0.58	96.9
Surfel Cut			0.73	97.5					0.69	98.7		
Zaharescu			0.55	99.2	0.78	95.8			0.42	98.6	0.45	99.2
Zaharescu2			0.62	98.5					0.5	98.5		
Zach			0.58	99.0					0.67	98.0		
Hernandez	0.36	99.7	0.52	99.5	0.75	95.3	0.49	99.6	0.45	97.9	0.6	98.5
SurfEvolution			0.56	98.9	0.78	96.8			0.56	97.7	0.66	97.6
Bradley			0.57	98.1	0.48	93.7			0.39	97.6	0.38	94.7
Sinha			0.79	94.9					0.69	97.2		
Kolev			0.79	96.0					0.53	96.9		
Vogiatzis	1.07	90.7	0.76	96.2	2.77	79.4	0.42	99.0	0.49	96.7	1.18	90.8
Auclair			0.86	96.2	1.03	92.5			0.62	96.7	0.74	96.8
JancosekCVWW									0.79	95.9		
Sormann			0.69	97.2					0.81	95.2		
Gargallo			0.88	84.3	1.05	81.9			0.6	92.9	0.76	90.7
Strecha			0.86	97.6	1.05	94.1			1.21	92.4	1.41	91.5
Tran			1.12	92.3	1.53	85.4			1.12	92.0	1.26	89.3
Continuous Probab			1.89	92.1					2.61	91.4		
Kolmogorov			1.86	90.4					2.81	86.0		
Merrell Confidence			0.83	88.0					0.84	83.1		
ICCV_1500	0.65	85.8	0.7	78.9	0.59	74.9	0.91	73.8	0.71	76.6	0.66	74.9
Merrell Stability			0.76	85.2					0.73	73.1		
Goesele	0.42	98.0	0.61	86.2	0.87	56.6	0.56	80.0	0.46	57.8	0.56	26.0
Campbell	0.41	99.9	0.48	99.4	0.53	98.6						
ContinuousDepth					0.65	96.9					0.51	98.7
Delaunoy					0.73	95.9					0.89	93.9
Goesele 2007	0.42	98.2					0.46	96.7				
Habbecke	0.66	98.0					0.43	99.7				
Hornung	0.58	98.7					0.79	95.1				
Ladikos											0.89	95.0
Liu					0.96	89.6					0.59	98.3

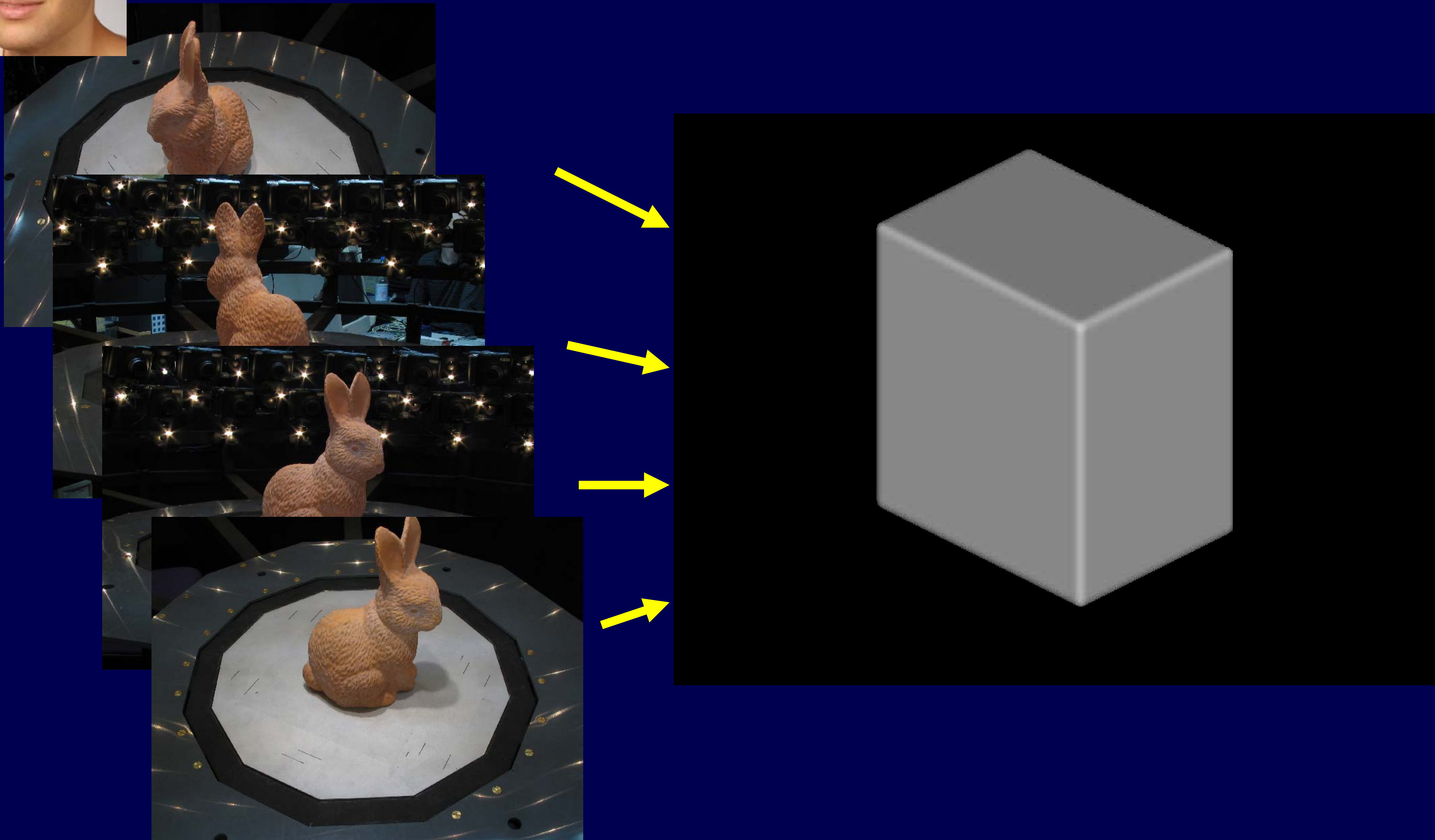
Kolev2 and Ground Truth



Multiple View Reconstruction

Kolev, Cremers, ECCV '08

Multiple View Reconstruction



Super-Resolution Texture Map

*Goldlücke, Cremers, ICCV '09, DAGM '09**

** Best Paper Award*

Super-Resolution Texture Map

Weighted average

Super-resolution texture

Goldlücke, Cremers, ICCV ’09, DAGM ‘09

Convex Multilabel Optimization

One of two images

Depth reconstruction

Pock, Schoenemann, Graber, Bischof, Cremers, ECCV '08

Convex Multilabel Optimization

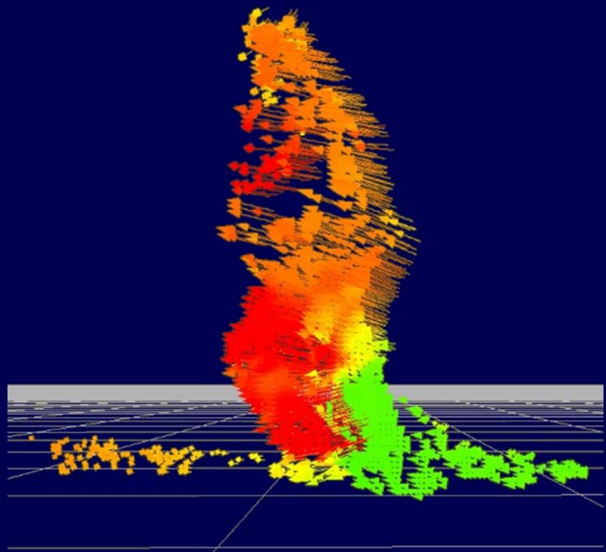
Input color image

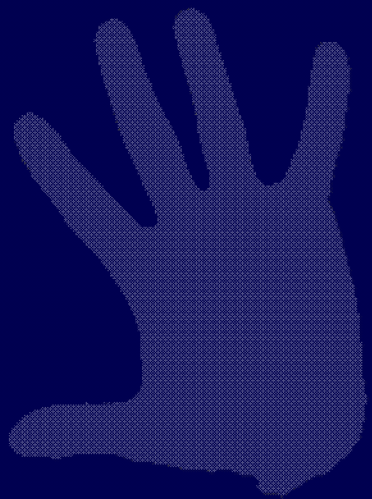
10 label segmentation

Pock, Chambolle, Bischof, Cremers, CVPR ’09

Overview


3D reconstruction


Motion analysis


Shape analysis


Segmentation & tracking

High Accuracy Motion Estimation

Input video

Realtime optical flow

High Accuracy Motion Estimation

Input video

Realtime optical flow *

* 30 fps at 640 x 480 resolution

Quantitative Performance

Optical flow evaluation results: Average end-point error - Mozilla Firefox

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http://vision.middlebury.edu/flow/eval/results/results-e1.html | middlebury optic flow

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Optical flow evaluation results

Statistics: Average SD R0.5 R1.0 R2.0 A50 A75 A95

Error type: angle end-point interpolation normalized interpolation

Wedel et al. ICCV '09 → Adaptive [25]

Average end-point error	avg. rank	Army (Hidden texture) all	Army disc	Army untext	Mequon (Hidden texture) all	Mequon disc	Mequon untext	Schefflera (Hidden texture) all	Schefflera disc	Schefflera untext	Wooden (Hidden texture) all	Wooden disc	Wooden untext	Grove (Synthetic) all	Grove disc	Grove untext	Urban (Synthetic) all	Urban disc	Urban untext	Yosemite (Synthetic) all	Yosemite disc	Yosemite untext	Teddy (Stereo) all	Teddy disc	Teddy untext
Adaptive [25]	5.0	0.09 1	0.26 1	0.06 1	0.23 7	0.78 6	0.18 6	0.54 11	1.19 13	0.21 5	0.18 1	0.91 3	0.10 1	0.88 4	1.25 4	0.73 6	0.50 2	1.28 2	0.31 2	0.14 11	0.16 13	0.22 10	0.65 3	1.37 3	0.79 4
Complementary OF [26]	6.4	0.11 6	0.28 5	0.10 10	0.18 1	0.63 2	0.12 1	0.31 4	0.75 4	0.18 1	0.19 2	0.97 5	0.12 4	0.97 11	1.31 6	1.00 12	1.78 21	1.73 8	0.87 16	0.11 5	0.12 3	0.22 10	0.68 4	1.48 4	0.95 8
Aniso. Huber-L1 [27]	7.1	0.10 3	0.28 5	0.08 3	0.31 15	0.88 10	0.28 15	0.56 13	1.13 10	0.29 15	0.20 5	0.92 4	0.13 7	0.84 3	1.20 3	0.70 2	0.39 1	1.23 1	0.28 1	0.17 17	0.15 11	0.27 18	0.64 2	1.36 2	0.79 4
DPOF [20]	7.2	0.13 15	0.35 15	0.09 5	0.25 8	0.79 7	0.19 7	0.24 1	0.49 1	0.21 5	0.19 2	0.62 1	0.15 13	0.74 1	1.09 1	0.49 1	0.66 7	1.80 12	0.63 9	0.19 20	0.17 16	0.35 23	0.50 1	1.08 1	0.55 1
Spatially variant [21]	7.5	0.10 3	0.27 4	0.08 3	0.22 5	0.75 5	0.19 7	0.43 7	1.00 8	0.18 1	0.19 2	1.05 7	0.10 1	1.05 12	1.41 15	1.16 14	0.59 5	1.61 6	0.43 4	0.13 7	0.11 1	0.28 19	0.96 14	1.72 13	1.28 16
TV-L1-improved [19]	8.4	0.09 1	0.26 1	0.07 2	0.20 4	0.71 4	0.16 2	0.53 10	1.18 12	0.22 7	0.21 8	1.24 14	0.11 3	0.90 5	1.31 6	0.72 3	1.51 15	1.93 13	0.84 12	0.18 19	0.17 16	0.31 20	0.73 8	1.62 9	0.87 7
Multicue MRF [23]	8.8	0.11 6	0.26 1	0.11 14	0.19 2	0.53 1	0.17 5	0.24 1	0.49 1	0.19 3	0.24 11	1.13 10	0.15 13	0.79 2	1.10 2	0.72 3	1.47 13	1.60 5	0.85 13	0.28 27	0.19 24	0.71 27	0.78 10	1.53 6	1.09 12
Occlusion bounds [28]	9.4	0.11 6	0.32 10	0.10 10	0.29 12	0.94 14	0.24 13	0.39 5	0.93 5	0.26 11	0.22 10	1.10 9	0.12 4	1.10 15	1.37 11	1.50 21	0.93 9	1.77 9	0.57 8	0.10 2	0.14 8	0.11 1	0.87 12	1.71 12	1.06 9
Rannacher [29]	9.8	0.11 6	0.31 8	0.09 5	0.25 8	0.84 9	0.21 10	0.57 15	1.27 18	0.26 11	0.24 11	1.32 17	0.13 7	0.91 7	1.33 8	0.72 3	1.49 14	1.95 15	0.78 10	0.15 13	0.14 8	0.26 13	0.69 6	1.58 8	0.86 6
Brox et al. [7]	9.9	0.11 6	0.32 10	0.11 14	0.27 11	0.93 12	0.22 11	0.39 5	0.94 6	0.24 9	0.24 11	1.25 15	0.13 7	1.10 15	1.39 13	1.43 19	0.89 8	1.77 9	0.55 7	0.10 2	0.13 5	0.11 1	0.91 13	1.83 15	1.13 14
Second-order prior [10]	10.2	0.11 6	0.31 8	0.09 5	0.26 10	0.93 12	0.20 9	0.57 15	1.25 17	0.26 11	0.20 5	1.04 6	0.12 4	0.94 8	1.34 9	0.83 10	0.61 6	1.93 13	0.47 6	0.20 21	0.16 13	0.34 22	0.77 9	1.64 10	1.07 11
F-TV-L1 [17]	10.6	0.14 16	0.35 15	0.14 18	0.34 16	0.98 15	0.26 14	0.59 17	1.19 13	0.26 11	0.27 16	1.36 18	0.16 15	0.90 5	1.30 5	0.76 8	0.54 3	1.62 7	0.36 3	0.13 7	0.15 11	0.20 9	0.68 4	1.56 7	0.66 2
Fusion [8]	11.0	0.11 6	0.34 13	0.10 10	0.19 2	0.69 3	0.16 2	0.29 3	0.66 3	0.23 8	0.20 5	1.19 12	0.14 11	1.07 13	1.42 16	1.22 15	1.35 10	1.49 4	0.86 15	0.20 21	0.20 25	0.26 13	1.07 17	2.07 19	1.39 19
Dynamic MRF [9]	13.4	0.12 14	0.34 13	0.11 14	0.22 5	0.89 11	0.16 2	0.44 8	1.13 10	0.20 4	0.24 11	1.29 16	0.14 11	1.11 17	1.52 20	1.13 13	1.54 16	2.37 25	0.93 17	0.13 7	0.12 3	0.31 20	1.27 21	2.33 23	1.66 20
CBF [14]	13.4	0.10 3	0.28 5	0.09 5	0.29 12	0.79 7	0.29 16	0.45 9	0.98 7	0.24 9	0.21 8	1.22 13	0.13 7	0.96 9	1.39 13	0.74 7	2.32 28	2.19 19	1.29 24	0.34 29	0.27 29	0.85 29	0.86 11	1.78 14	1.06 9
SegOF [12]	13.6	0.15 17	0.36 17	0.10 10	0.57 18	1.16 18	0.59 23	0.68 18	1.24 15	0.64 17	0.32 18	0.86 2	0.26 18	1.18 20	1.50 19	1.47 20	1.63 19	2.09 16	0.96 18	0.08 1	0.13 5	0.12 3	0.70 7	1.50 5	0.69 3
Learning Flow [13]	15.6	0.11 6	0.32 10	0.09 5	0.29 12	0.99 16	0.23 12	0.55 12	1.24 15	0.29 15	0.36 19	1.56 20	0.25 17	1.25 22	1.64 23	1.41 18	1.55 18	2.32 24	0.85 13	0.14 11	0.18 21	0.24 12	1.09 18	2.09 21	1.27 15
Filter Flow [22]	16.5	0.17 19	0.39 19	0.13 17	0.43 17	1.09 17	0.38 17	0.75 19	1.34 19	0.78 22	0.70 22	1.54 19	0.68 22	1.13 19	1.38 12	1.51 22	0.57 4	1.32 3	0.44 5	0.22 24	0.23 27	0.26 13	0.96 14	1.66 11	1.12 13
GraphCuts [16]	17.2	0.16 18	0.38 18	0.14 18	0.59 21	1.36 22	0.46 18	0.56 13	1.07 9	0.64 17	0.26 15	1.14 11	0.17 16	0.96 9	1.35 10	0.84 11	2.25 27	1.79 11	1.22 23	0.22 24	0.17 16	0.43 25	1.22 20	2.05 18	1.78 22
Black & Anandan 3 [6]	17.6	0.18 20	0.42 20	0.19 22	0.58 20	1.31 20	0.50 19	0.95 23	1.58 22	0.70 19	0.49 20	1.59 21	0.45 20	1.08 14	1.42 16	1.22 15	1.43 11	2.28 22	0.83 11	0.15 13	0.17 16	0.17 6	1.11 19	1.98 17	1.30 17
SPSA-learn [15]	18.1	0.18 20	0.45 21	0.17 20	0.57 18	1.32 21	0.51 20	0.84 20	1.50 20	0.72 20	0.52 21	1.64 22	0.49 21	1.12 18	1.42 16	1.39 17	1.75 20	2.14 17	1.06 21	0.13 7	0.13 5	0.19 7	1.32 22	2.08 20	1.73 21
GroupFlow [11]	18.7	0.21 22	0.51 22	0.21 23	0.79 25	1.69 26	0.72 25	0.86 21	1.64 23	0.74 21	0.30 17	1.07 8	0.26 18	1.29 24	1.81 25	0.82 9	1.94 22	2.30 23	1.36 25	0.11 5	0.14 8	0.19 7	1.06 16	1.96 16	1.35 18
2D-CLG [3]	20.5	0.28 26	0.62 27	0.21 23	0.67 24	1.21 19	0.70 24	1.12 25	1.80 26	0.99 25	1.07 27	2.06 25	1.12 27	1.23 21	1.52 20	1.62 25	1.54 16	2.15 18	0.96 18	0.10 2	0.11 1	0.16 5	1.38 23	2.26 22	1.83 23
Horn & Schunck [5]	21.8	0.22 24	0.55 25	0.22 25	0.61 22	1.53 24	0.52 21	1.01 24	1.73 24	0.80 23	0.78 24	2.02 24	0.77 24	1.26 23	1.58 22	1.55 24	1.43 11	2.59 26	1.00 20	0.16 16	0.18 21	0.15 4	1.51 24	2.50 24	1.88 24
Black & Anandan 2 [2]	21.9	0.21 22	0.52 23	0.17 20	0.65 23	1.52 23	0.58 22	0.93 22	1.54 21	1.03 26	0.76 23	1.97 23	0.73 23	1.40 25	1.80 24	1.54 23	2.04 24	2.22 20	1.12 22	0.15 13	0.17 16	0.26 13	1.68 25	2.64 25	2.06 25
Black & Anandan [1]	25.4	0.26 25	0.54 24	0.27 26	0.99 26	1.61 25	1.07 26	1.23 26	1.77 25	1.14 28	0.98 25	2.10 26	0.97 25	1.59 28	1.97 28	1.95 26	2.19 26	2.26 21	1.41 27	0.20 21	0.18 21	0.41 24	2.34 26	3.46 28	2.98 26
STOB [24]	25.5	0.30 28	0.70 28	0.36 28	1.09 27	1.77 27	1.21 27	1.25 28	1.98 28	1.03 26	1.56 28	2.26 28	1.71 28	1.54 27	1.82 26	2.14 28	2.02 23	2.79 28	1.36 25	0.17 17	0.16 13	0.26 13	2.43 27	3.18 26	3.31 27
FOLKI [18]	27.0	0.29 27	0.73 29	0.33 27	1.52 28	1.96 29	1.80 28	1.23 26	2.04 29	0.95 24	0.99 26	2.20 27	1.08 26	1.53 26	1.85 27	2.07 27	2.14 25	3.23 29	1.60 28	0.26 26	0.21 26	0.68 26	2.67 28	3.27 27	4.32 28
Pyramid LK [4]	28.5	0.39 [illegible]	0.61 [illegible]	0.61 [illegible]	1.67 [illegible]	1.78 [illegible]	2.00 [illegible]	1.50 [illegible]	1.97 [illegible]	1.38 [illegible]	1.57 [illegible]	2.39 [illegible]	1.78 [illegible]	2.94 [illegible]	3.72 [illegible]	2.98 [illegible]	3.33 [illegible]	2.74 [illegible]	2.43 [illegible]	0.30 [illegible]	0.24 [illegible]	0.73 [illegible]	3.80 [illegible]	5.08 [illegible]	4.88 [illegible]

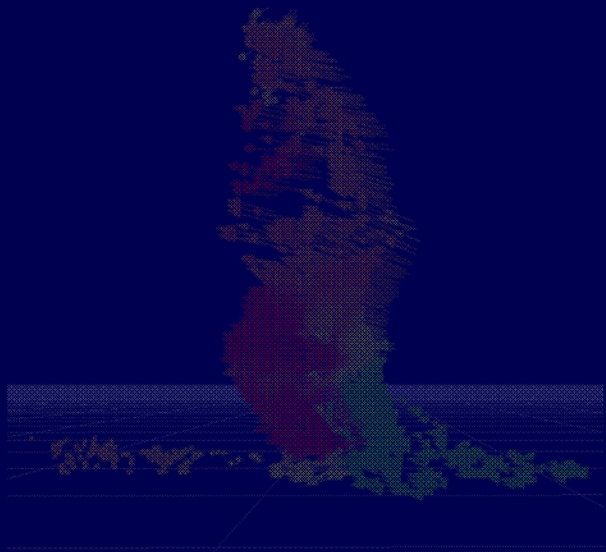
Scene Flow: Motion & 3D Structure

In collaboration with Daimler Research

Wedel et al., ECCV ’08

Overview

3D reconstruction

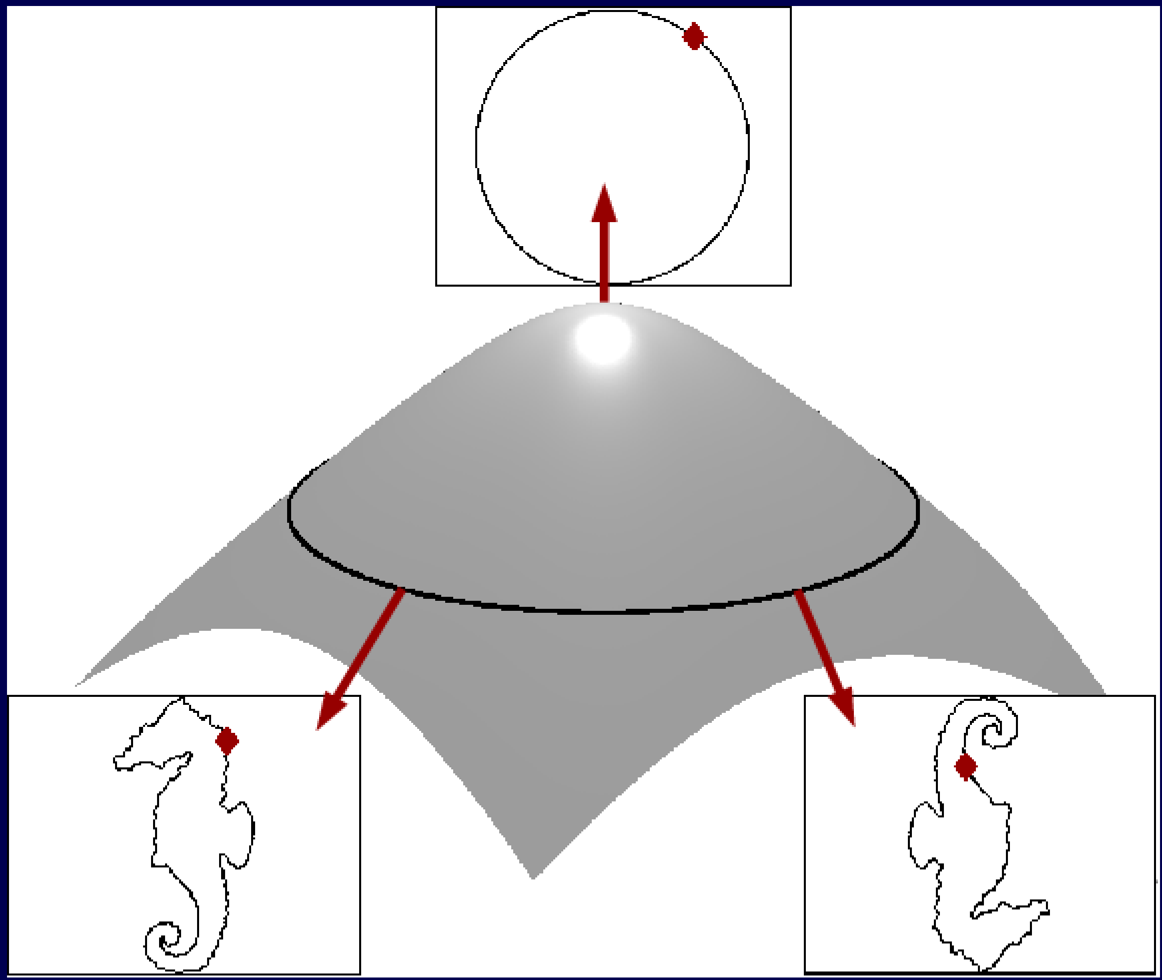


Motion analysis

Shape analysis

Segmentation & tracking

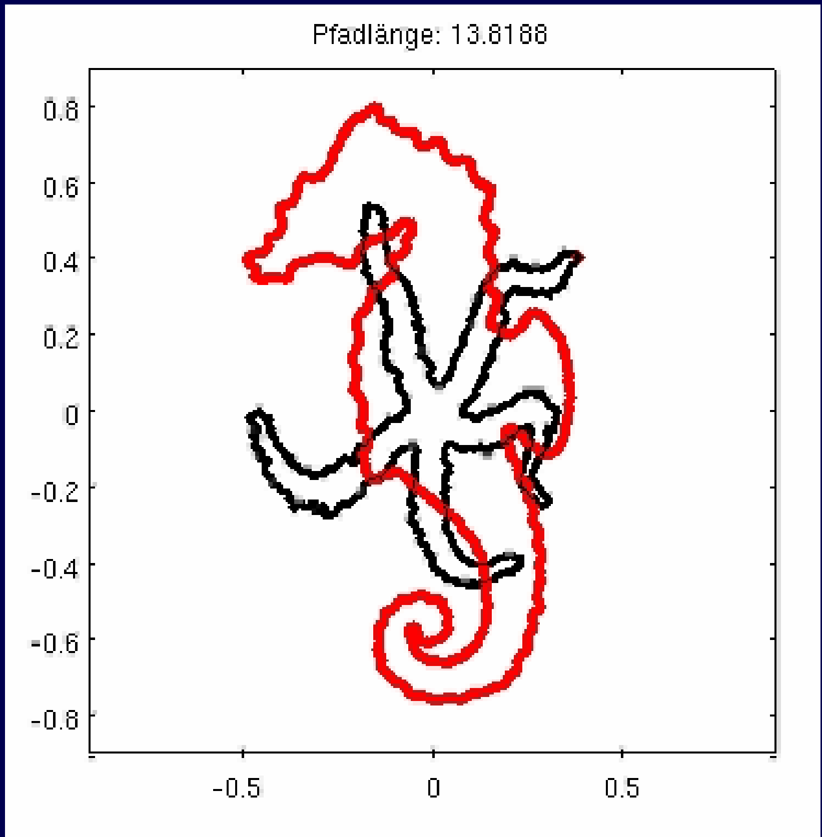
Shape Similarity via Geodesics



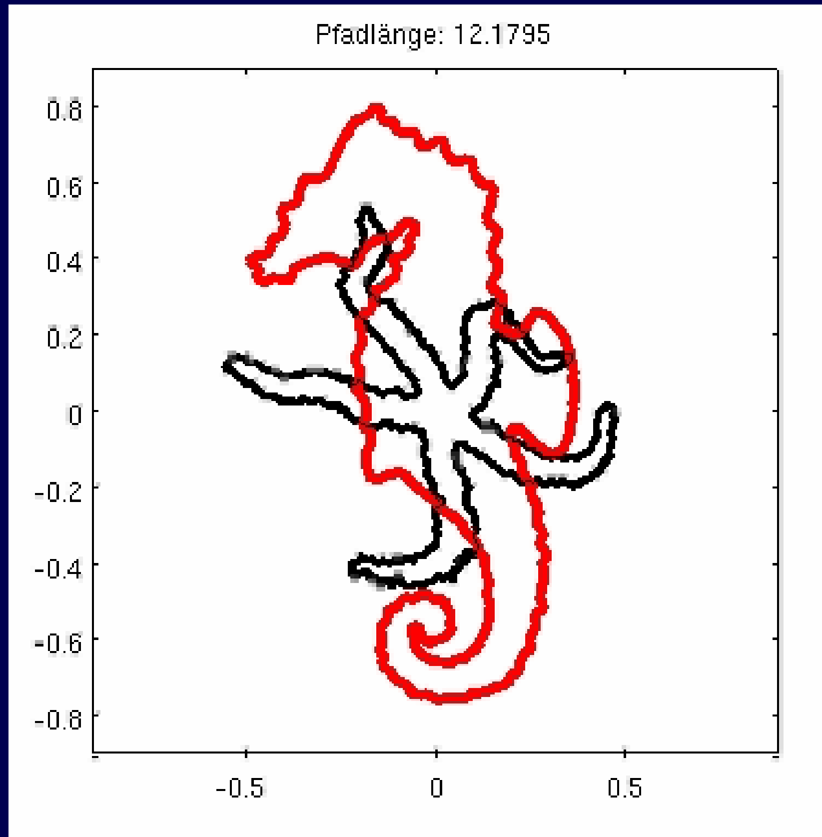
Klassen et al., PAMI '03:
Shape similarity as length of the shortest path (geodesic)

Shape Similarity via Geodesics

Schmidt, Clausen, Cremers DAGM '06



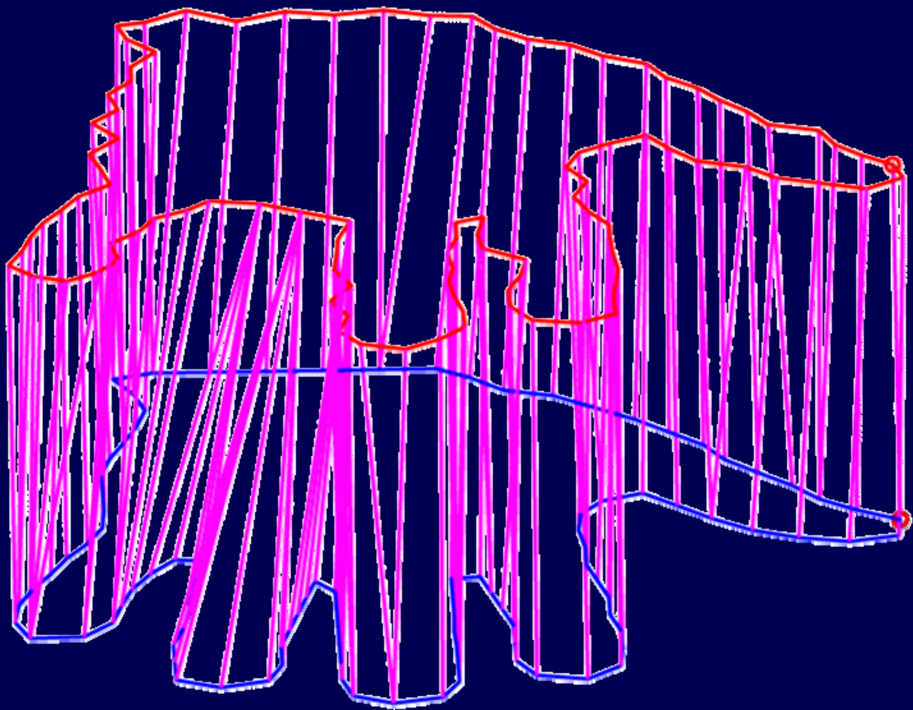
Shooting Methode



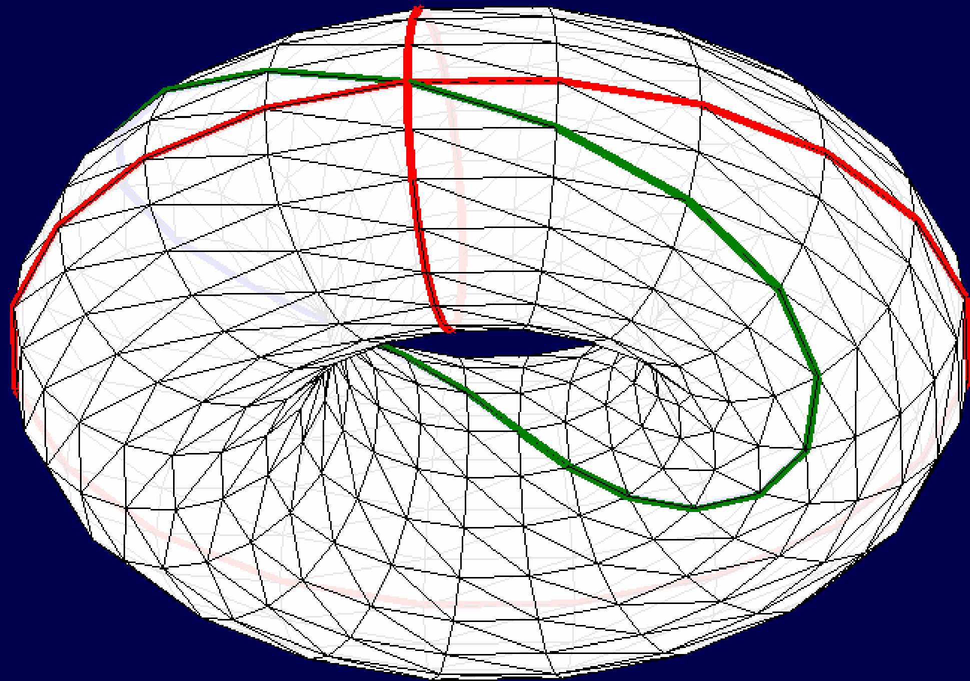
Variational length minimization

symmetric, stable, 1000 x faster

Optimal Matching & Correspondence



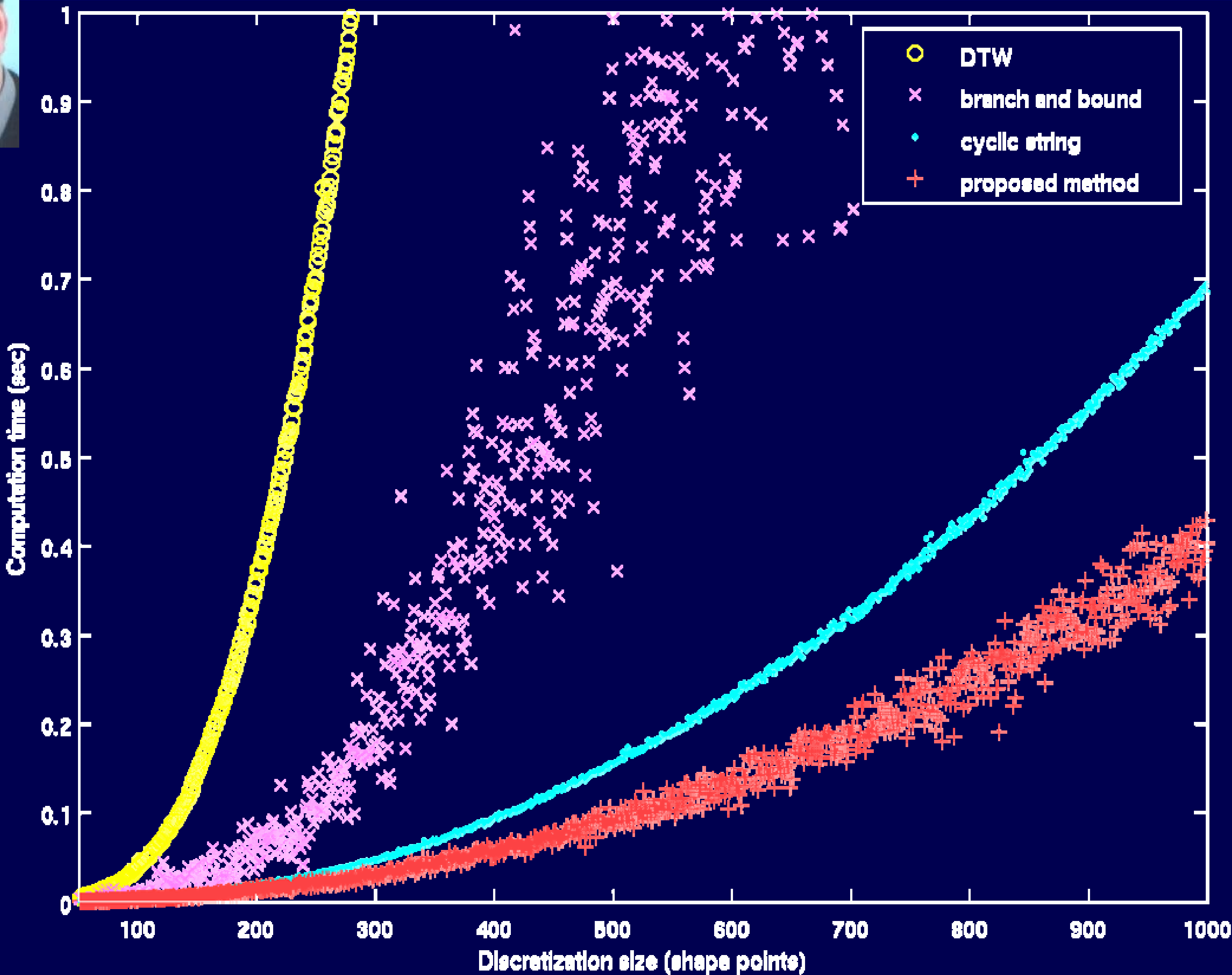
Optimal correspondence between
Points of similar curvature



Matching as shortest cylic path

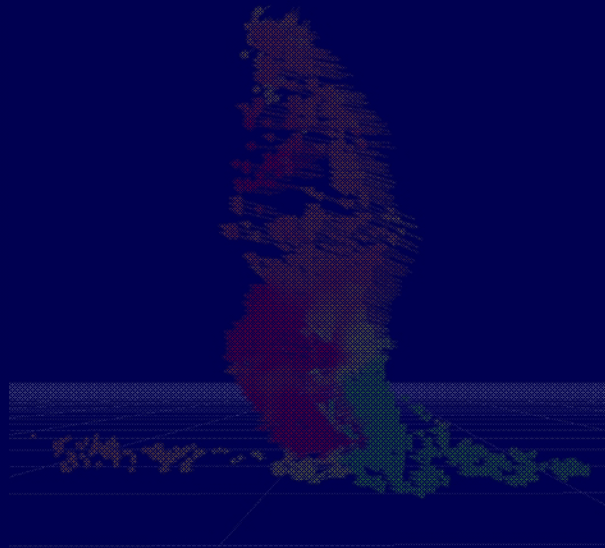
Schmidt, Farin, Cremers, ICCV '07

Fast Matching in Subcubic Runtime

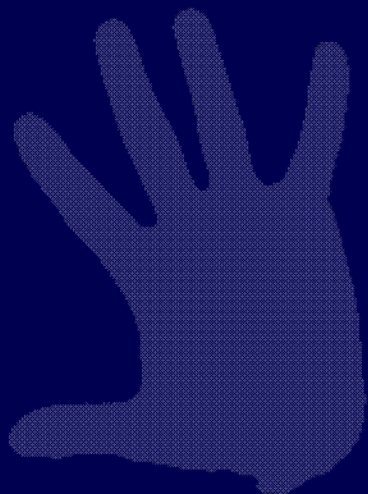


Overview

3D reconstruction



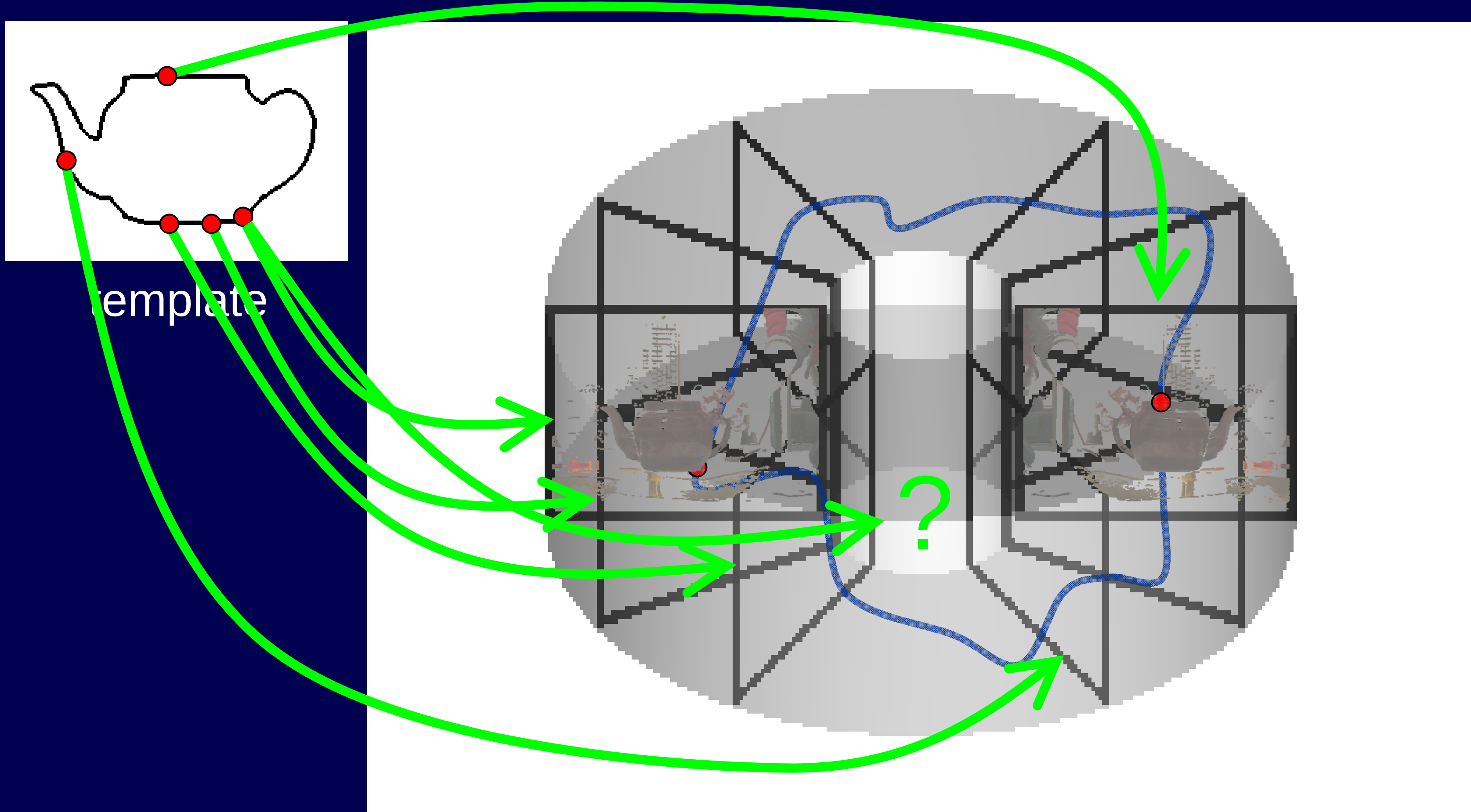
Motion analysis



Shape analysis

Segmentation & tracking

Globally Optimal Tracking



Schoenemann, Cremers ICCV 2007, PAMI 2009

Theorem: Any matching of the template to the image corresponds to a cyclic path in the product space of template and image.

Globally Optimal Tracking

3 fps

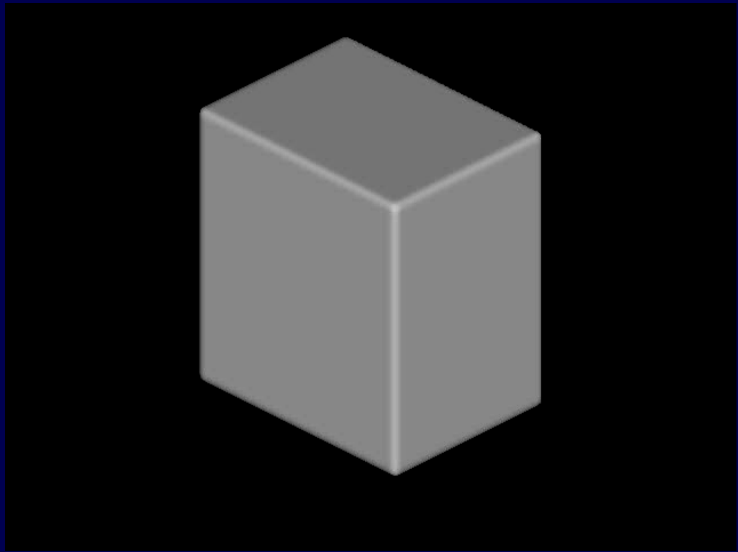
25 fps

Schoenemann & Cremers CVPR ’08:

Real-time by parallel implementation of polynomial algorithm.

Globally Optimal Tracking

Summary



Multiple view reconstruction

Super-resolution texturing

Scene flow estimation

Tracking deformable shapes