Real-Time Camera Tracking and 3D Reconstruction Using Signed Distance Functions

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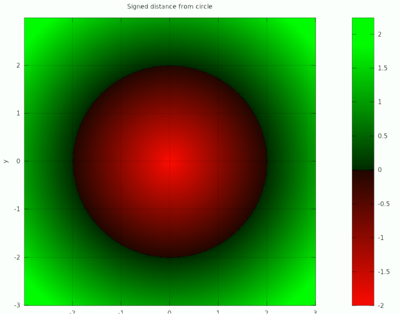
The Paper

- Title: Real-Time Camera Tracking and 3D Reconstruction Using Signed Distance Functions
- Published in 2013
- Authors:
  - Bylow, Erik
  - Sturm, Jürgen
  - Kerl, Christian
  - Kahl, Fredrik
  - Cremers, Daniel
- Features new real-time SLAM approach using an RGB-D sensor

Signed Distance Functions

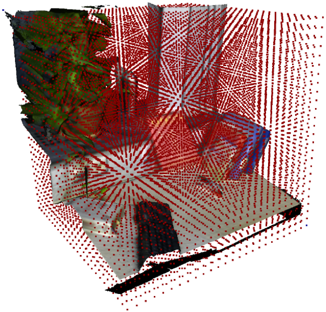
- definition in 3D: $\psi : \mathbb{R}^3 \rightarrow \mathbb{R}$
- **intuitive definition**:
  "distance to **nearest surface**"
- sign of function:
  - negative inside objects
  - positive outside objects
  - 0 on object surface



Credit: *Daniel Canelhas*

Function Representation

- Purpose: representation of the **geometry being mapped**
- Voxel grids D, W of resolution m



Credit: *Erik Bylow et al.*

Camera Tracking

- **Given**: depth image, where
  - $I_d(i,j)$ = depth of pixel i,j, and
  - $x_{ij} \in \mathbb{R}^3$ = local coordinate of the surface captured in pixel i,j
- **Goal**: find camera pose that maximises likelihood of observing depth:

$$p(I_d \mid R, t) \propto \prod_{i,j} \exp(-\underbrace{\psi(Rx_{ij} + t)}_{0 \text{ if correct pose}}{}^2)$$

Optimisation Procedure

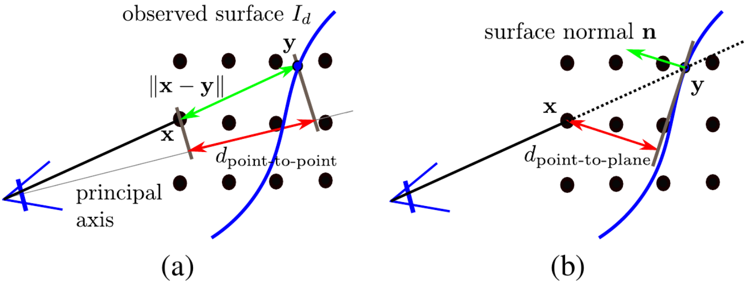
- Corresponding **error function** to be minimised:

$$E(R, t) = \sum_{i,j} \psi(Rx_{ij} + t)^2$$

- Non-linear least-squares problem $\Rightarrow$ Optimised using **Gauss-Newton** method
- Computation for each i, j of update-step **in parallel** on GPU

Distance Function Approximations

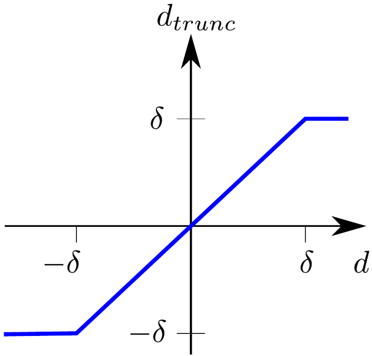
- Calculation of **actual distance** to nearest surface: **expensive**
- Instead ⇒ **approximative** distance functions:
  - projective **point-to-point** (a)
  - projective **point-to-plane** (b)



Credit: *Erik Bylow et al.*

Distance Truncation

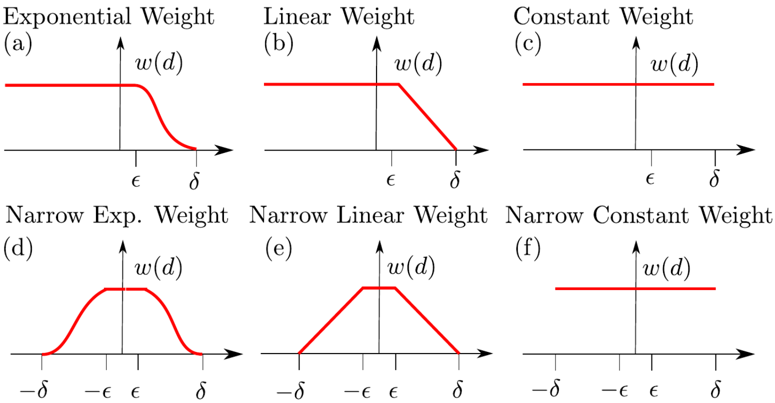
- Larger distances lead to less accurate approximations
- Mainly interested in zero-crossing of SDF
  - ⇒ Truncation of distance so that $|d| \leq \delta$



Credit: *Erik Bylow et al.*

Weighting Functions

- distance values more reliable for voxels **in front of** the surface



Credit: *Erik Bylow et al.*

Data Fusion and 3D-Reconstruction

- **Given**: Distance + weighting measurements d_i, w_i for each observed frame i
- **Goal**: parametrise ψ to maximise observation likelihood for n observed frames:

$$p(d_1, w_1, ..., d_n, w_n|\psi) \propto \prod_{i=1}^{n} exp(-\frac{1}{2}w_i(\psi - d_i)^2)$$

Update Step

- Reformulation and solving for max ⇒ **closed form solution**:

$$\psi = \frac{\sum_{i=1}^{n} w_i d_i}{\sum_{i=1}^{n} w_i}$$

⇒ Distance values as running weighted average:

$$D \leftarrow \frac{WD + w_{n+1} d_{n+1}}{W + w_{n+1}}$$

$$W \leftarrow W + w_{n+1}$$

Method Comparison: Accuracy

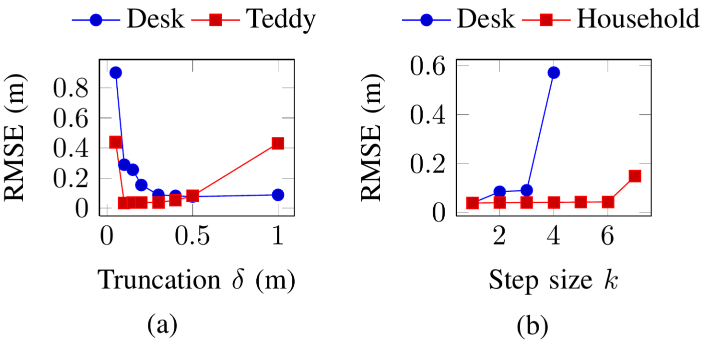
- Compared methods: Kinect Fusion and RGB-D SLAM
- Error metric: root mean square absolute trajectory error

Method	Res.	Teddy	F1 Desk	F1 Desk2	F3 Household	F1 Floor
KinFu	256	0.156 m	0.057m	0.420 m	0.064 m	Failed
KinFu	512	0.337 m	0.068 m	0.635 m	0.061 m	Failed
Point-To-Plane	256	**0.072 m**	0.087 m	0.078 m	0.053 m	0.811 m
Point-To-Plane	512	0.101 m	0.059 m	0.623 m	0.053 m	0.640 m
Point-To-Point	256	0.086 m	0.038 m	**0.061 m**	**0.039 m**	0.641 m
Point-To-Point	512	0.080 m	**0.035 m**	0.062 m	0.040 m	**0.567 m**
RGB-D SLAM		0.111 m	0.026 m	0.043 m	0.059 m	0.035 m

Credit: *Erik Bylow et al.*

Truncation and Frame Skipping

- Performance for different truncation values δ (a)
- Effect of skipping frames to simulate faster camera motion (b)



Credit: *Erik Bylow et al.*

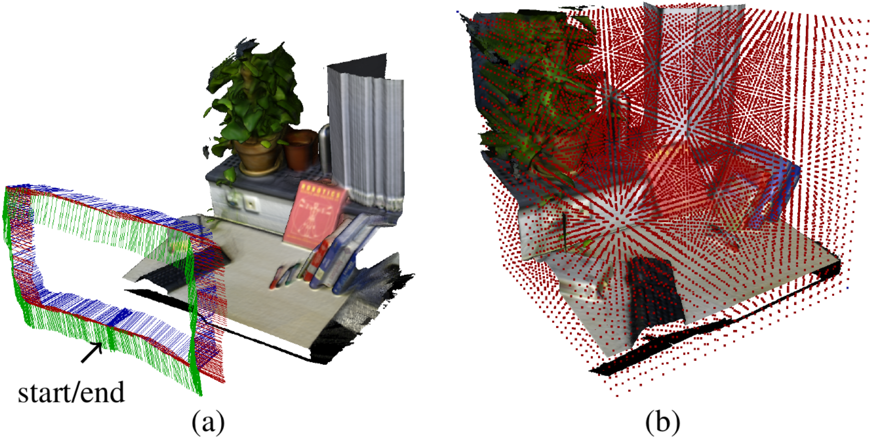
Weighting Function Comparison

- Exponential weighting function: comparatively more robust
- Narrow Weighting functions: typically less accurate

Dataset	F1 Teddy		F1 Desk	
	RMSE	Max	RMSE	Max
Exp. Weight	0.088 m	**0.213 m**	**0.038 m**	0.088 m
Linear Weight	**0.083 m**	0.285 m	**0.038 m**	0.089 m
Constant Weight	0.093 m	0.242 m	0.040 m	0.089 m
Narrow Exp.	0.170 m	0.414 m	**0.038 m**	**0.083 m**
Narrow Linear	0.382 m	0.688 m	0.044 m	0.085 m
Narrow Constant	0.379 m	0.694 m	0.044 m	0.209 m

Credit: *Erik Bylow et al.*

Qualitative Results



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Questions / Discussion