V'''D'' Workshop 2003 Frankfurt

3D Model Retrieval

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DFG Teilprojekt „Ähnlichkeitssuche durch Gestaltcharakterisierung auf 3D Datenbanken"

DFG SPP V3D2 Phase 3

Joint project of

Multimedia Signal Processing Group

Prof. Dietmar Saupe

Dejan V. Vranić (starting date: April 2002)

Databases, Data Mining and Visualization Group

Prof. Daniel Keim

Tobias Schreck (starting date: November 2002)

University of Konstanz, Dept. of Comp. Science

Overview

Part A: 3D Model Retrieval (Dejan V. Vranić)

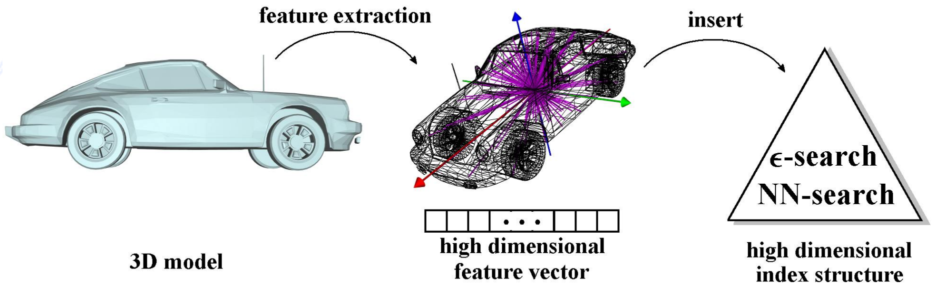
- Problem of 3D Model Retrieval
- Requirements
- Approach
- Demo
- Exposition of a small group of feature vectors

Part B: Kombination von Feature-Vektoren (Tobias Schreck)

- Problemstellung
- Untersuchungsansatz
- Effektivitätsresultate
- Entwicklungsziel: Query Processor

Content-based retrieval

- **Goal**
  - Use a multimedia object (image, movie clip, audio file, or 3D-model) as a key;
- **Approach**
  - Extract appropriate features (descriptors (D)) from objects automatically and use them as points in a search space;



Typical retrieval algorithm

- **Normalization**
  - Problem: 3D objects are defined in arbitrary coordinates and units;
- **Feature Extraction**
  - Problem: describe object in few variables yet with sufficient discriminant power;
- **Similarity search**
  - Problem: for a given query object efficiently find nearest neighbors (curse of dimensionality).

3D-shape descriptors criteria

- **Invariance with respect to translation, rotation, scaling, and reflections;**
- **Robustness with respect to level-of-detail (different tessellations);**
- **Robustness with respect to noise and outliers;**
- **Efficient feature extraction and retrieval;**
- **Multiresolution feature representation;**
- **Discriminating of shape similarities.**

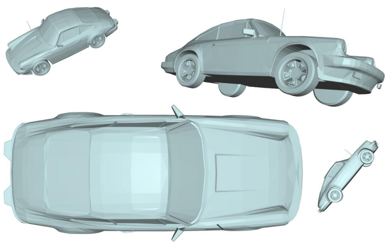
Demo

Invariance w.r.t. similarity transforms

Three approaches:

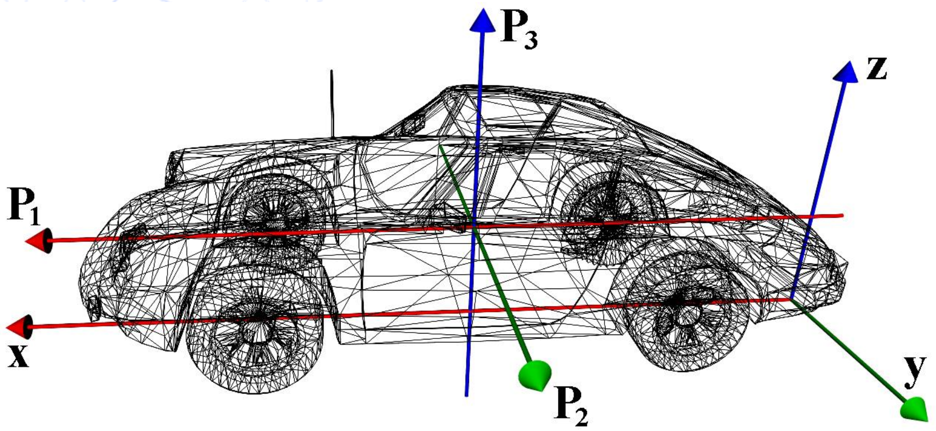
- ♦ **Finding canonical coordinate frame**
  - Principle Component Analysis (PCA);
- ♦ **Aligning objects pairwise**
  - Fitting objects (time-consuming);
- ♦ **Defining Ds that possess the invariance inherently**
  - Considering some relative features of sets of points or triangles (curvature spectrum, “shape distributions”, representation of topology);
  - By summing up (or averaging) features over a group of transformations (e.g., FFT on a sphere).

Normalization (pose estimation)

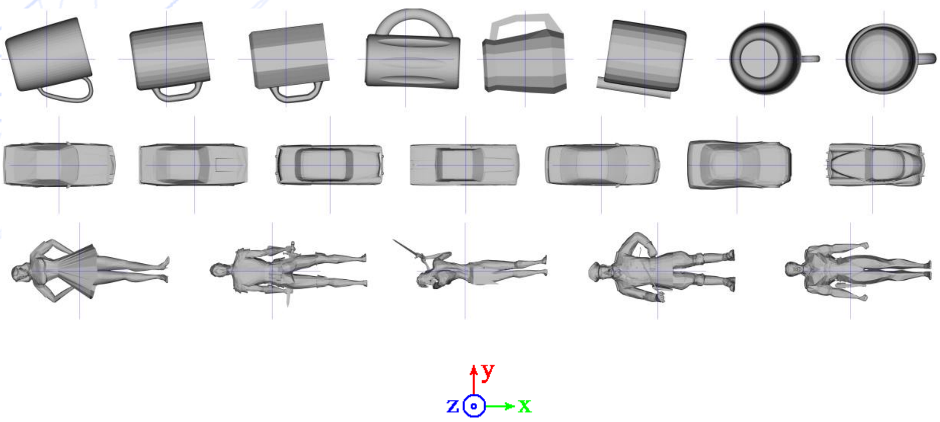


- ♦ **Purpose**
  - Finding a canonical frame (i.e., position and orientation);
- ♦ **Result**
  - Translation, rotation, scaling, and reflection invariance of descriptors;
- ♦ **Tools**
  - Center of mass,
  - “Continuous” PCA (CPCA) (rotation),
  - Test based on moments (reflections), and
  - Formula for calculating the scale factor.

The outcome of the CPCA



Examples of pose estimation using the CPCA



3D-shape descriptors

Classification of our 3D-shape descriptors:

- **Geometry-based**
  - Volume,
  - Voxel, and
  - Moment-based Ds;
- **Image-based**
  - Ray-based,
  - Depth-buffer,
  - Silhouette,
  - Shading, and
  - “Complex” Ds.

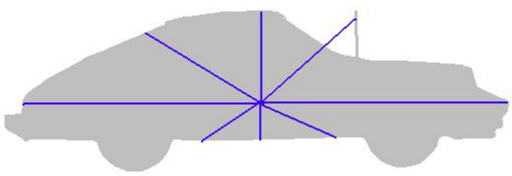
Representation: spatial or frequency (spectral) domain.

Ray-based D (spatial domain)

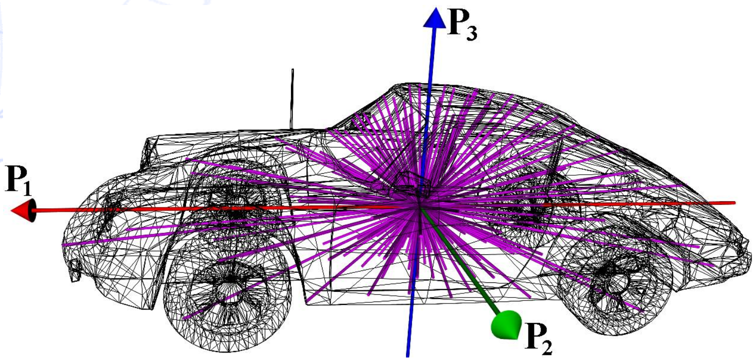
- **Idea**
  - Sample a 3D-model in regularly spaced directions and treat these samples as components of a feature vector.
- **Realization**
  - Measure extent of a model

$$r : S^2 \to R$$
$$\mathbf{u} \mapsto \max\{r \geq 0 \mid r\mathbf{u} \in I \cup \{\mathbf{0}\}\},$$

$\mathbf{u}$ – a directional unit vector
I – the point set of the model



Ray-based feature vector



Features as functions on a sphere

[Saupe, Vranić, MMSP 2001, DAGM 2001]

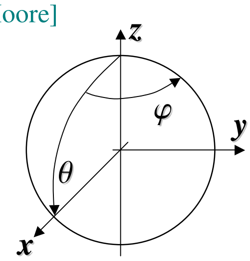
- **Spherical harmonics**
  - Use Fourier coefficients of a function on the 2-sphere to form a feature vector with an embedded multiresolution representation;
- **Realization**
  - Sample a 3D-model in appropriate radial directions $\mathbf{u}_{ij}$ $(i, j = 0,..., n\ -1)$ and treat these samples as values of a function on the 2-sphere.

Spherical harmonics

[Heally, Rockmore, Kostelec, Moore]

- **Functions on the 2-sphere**

$$f: S^2 \to \mathbb{C}$$
$$(\theta,\varphi) \to f(\theta,\varphi),$$
$$0 \le \theta \le \pi,$$
$$0 \le \varphi < 2\pi;$$



- **Spherical harmonics Y_l^m: $S^2 \to \mathbb{C}$, $|m| \le l$ provide orthonormal basis of $L^2(S^2)$;**

- **Subspace X_l spanned by $\{ Y_l^m \mid -l \le m \le l \}$ is invariant w.r.t. rotations of the sphere;**

Spherical harmonics visualization

(Courtesy of Quantum Chemistry Group, University of Oviedo)

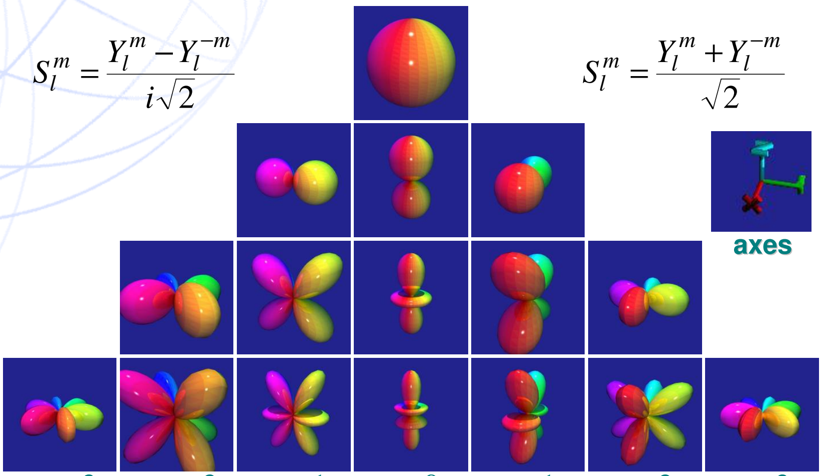
$$S_l^m = \frac{Y_l^m - Y_l^{-m}}{i\sqrt{2}} \qquad S_l^m = \frac{Y_l^m + Y_l^{-m}}{\sqrt{2}}$$

l=0

l=1

l=2

l=3



m=-3 *m*=-2 *m*=-1 *m*=0 *m*=1 *m*=2 *m*=3

$$S_l^0 = Y_l^0$$

Fourier transform on the sphere

- Expansion of the function $f(\theta,\varphi)$

$$f \approx \sum_{l \geq 0} \sum_{|m| \leq l} c(l,m) \cdot Y_l^m ;$$

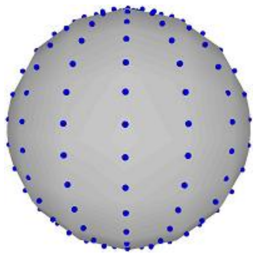
- $c(l,m) = \langle f, Y_l^m \rangle$ is (l,m) - Fourier coefficient;
- Use special FFT algorithms (Healy et al), public domain source code.

Frequency domain representation

$I =$ point set of (filled – in) triangles ,

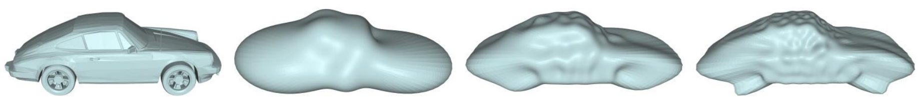
$r : S^2 \to R$

$\mathbf{u} \mapsto \max\{ r \geq 0 \mid r\mathbf{u} \in I \cup \{\mathbf{0}\} \},$



$$\mathbf{u}_{ij} = (x_{ij}, y_{ij}, z_{ij}) = (\cos\varphi_i \sin\theta_j, \sin\varphi_i \sin\theta_j, \cos\theta_j),$$

$$\varphi_i = 2i\pi / n, \qquad \theta_j = (2j+1)\pi / 2n, \qquad i, j = 0,\ldots,n-1.$$



Original　　8^2 harmonics　　16^2 harmonics　　24^2 harmonics

Absolute values of coefficients

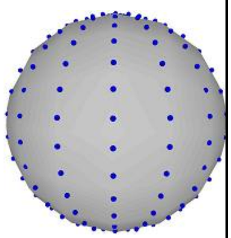
$c(l,m) = \overline{c(l,-m)} \Rightarrow |c(l,m)| = |c(l,-m)|$

$l = 0$				1.161			
$l = 1$			0.064	0.163	0.064		
$l = 2$		0.213	0.037	0.373	0.037	0.213	
$l = 3$	0.017	0.008	0.010	0.008	0.010	0.008	0.017
	m=-3	m=-2	m=-1	m=0	m=1	m=2	m=3

Dimension: $n\,(n + 1) / 2,\ l < n$.

"Complex" feature vector

[Vranić, Saupe ICME 2002]



I = point set of (filled−in) triangles,

$\mathbf{u}_{ij} = (x_{ij}, y_{ij}, z_{ij}) = (\cos\varphi_i \sin\theta_j, \sin\varphi_i \sin\theta_j, \cos\theta_j),$

$\varphi_i = 2i\pi / n,\quad \theta_j = (2j+1)\pi / 2n,\quad i, j = 0, \ldots, n-1,$

$r : S^2 \to \mathbb{C}$

$r(\mathbf{u}) = x(\mathbf{u}) + i\, y(\mathbf{u}),$

$x : S^2 \to [0,+\infty) \in \mathbb{R},\ y : S^2 \to [0,1] \in \mathbb{R},$

$$x(\mathbf{u}) = \max\{\, x \geqslant 0 \mid x\,\mathbf{u} \in I \cup \{\mathbf{0}\}\},\qquad y(\mathbf{u}) = \begin{cases} 0, & \text{if } x(\mathbf{u}) = 0 \\ \mathbf{u}\cdot\mathbf{n}(\mathbf{u}), & \text{otherwise} \end{cases}.$$

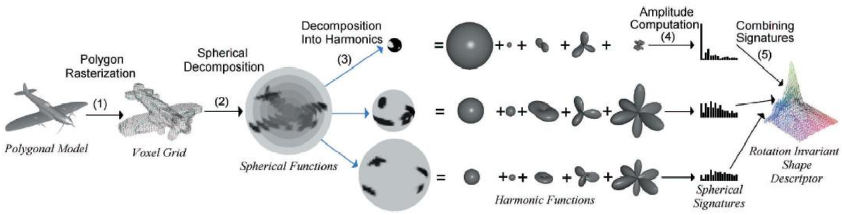
◆ **Find spherical power spectrum for $r(\mathbf{u})$ and for $l<n$ use *all* coefficient magnitudes as components of the feature vector**

Dimension: $n^2,\ l < n$.

Related work

- **[Paquet et al. '98]**
  - Cords-based, moments-based, and wavelet transform-based descriptors (Ds);
- **[Suzuki et al. '00]**
  - Grid-based and "rotation invariant" Ds;
- **[MPEG-7]**
  - 3D shape spectrum and 2D-3D multiple view;
- **[Hilaga et al. '01]**
  - Topology matching;
- **[Funkhouser et al. '01, '02, '03]**
  - Reflective symmetry, shape distribution, spherical harmonics, skeletal graphs.

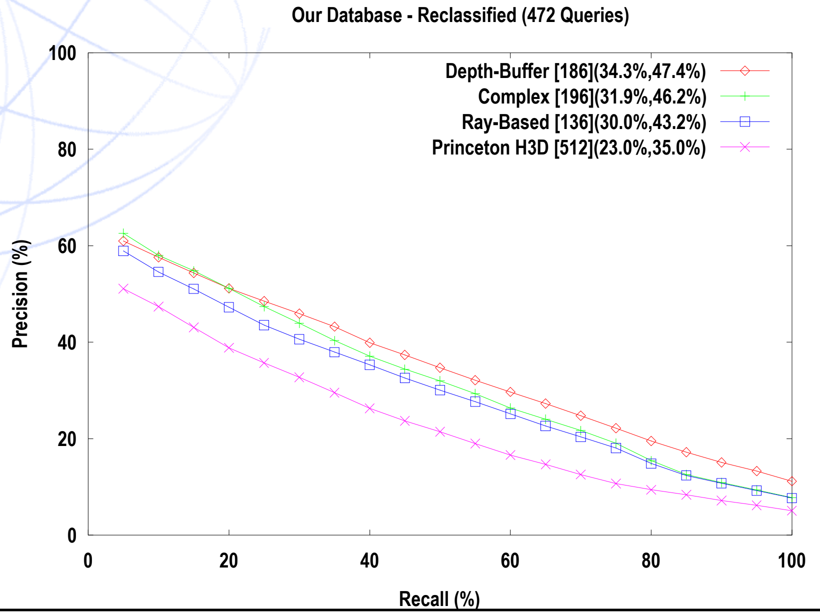
Harmonic 3D descriptor (H3D)



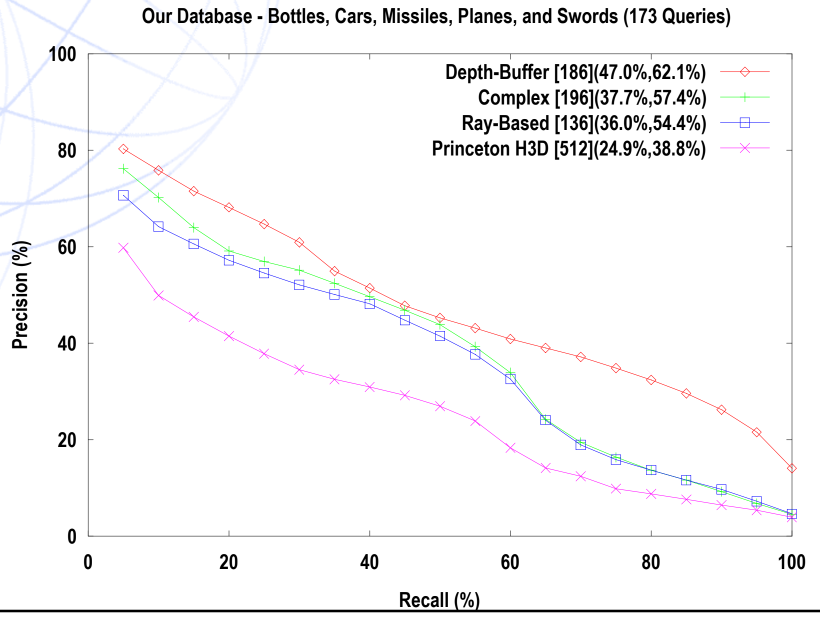
- **Spherical harmonics Y_l^m: $S^2 \to \mathbb{C}$, $|m| \le l$ provide orthonormal basis of $L^2(S^2)$;**
- **Subspace X_l spanned by $\{ Y_l^m \mid -l \le m \le l \}$ is invariant w.r.t. rotations of the sphere;**

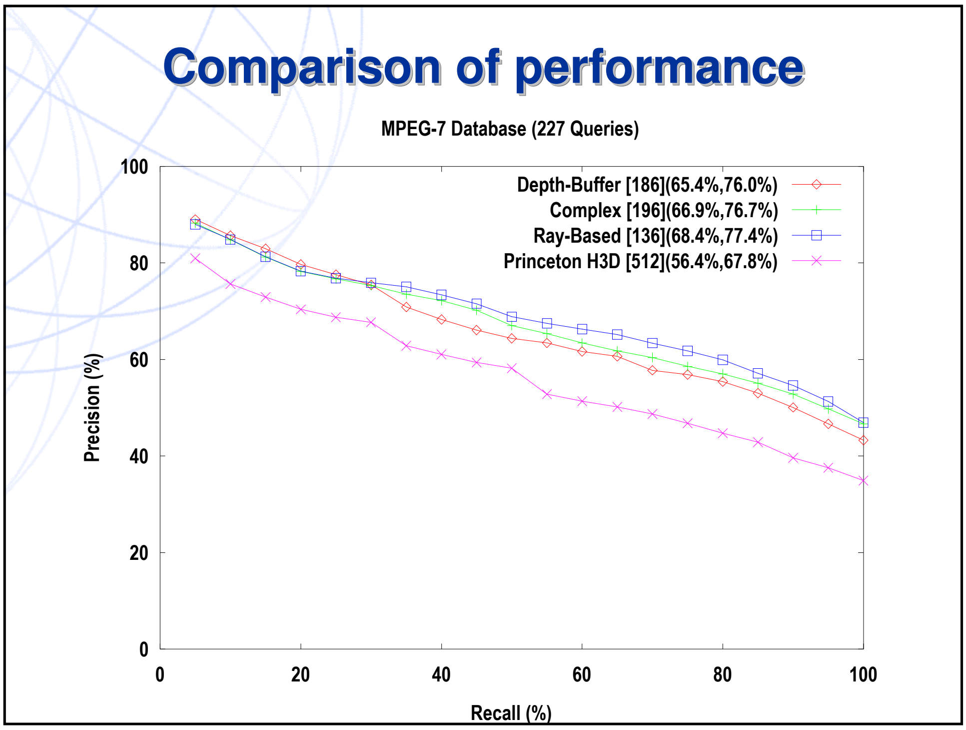
$$f_{i,l} = \sqrt{\sum_{|m| \le l} |c_i(l,m)|^2}, \quad 0 \le l < n, \; 1 \le i \le R$$

Comparison of performance

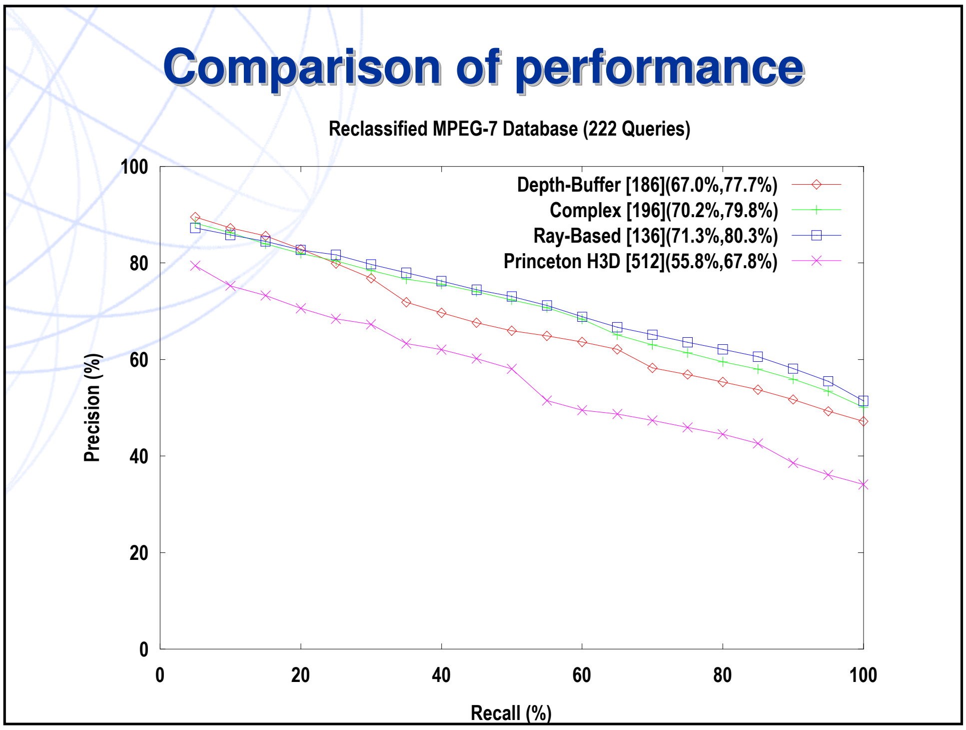


Comparison of performance





Comparison of performance
MPEG-7 Database (227 Queries)
Depth-Buffer [186](65.4%,76.0%)
Complex [196](66.9%,76.7%)
Ray-Based [136](68.4%,77.4%)
Princeton H3D [512](56.4%,67.8%)
Precision (%)
Recall (%)



Comparison of performance
Reclassified MPEG-7 Database (222 Queries)
Depth-Buffer [186](67.0%,77.7%)
Complex [196](70.2%,79.8%)
Ray-Based [136](71.3%,80.3%)
Princeton H3D [512](55.8%,67.8%)
Precision (%)
Recall (%)