A Survey of Simple Geometric Primitives Detection Methods for Captured 3D Data

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Context

Captured 3D Data → Primitive Detection → Abstraction → High Level Model
Context

Geometric Primitives → Simple 3D Shapes

- **High-level** and **compact** description of complex objects, Visual summary
- **Simplification** of geometry and topology: Make subsequent analysis **easier**
- **Accurate** representation: Geometric **substitute**
- **Spatial** **relationships**
Context

**Historical Background**

- **1960s**: 3D capture
- **1972**: Polyhedron fitting [Shirai, 1972]
- **1975**: Cylinder fitting [Popplestone et al., 1975]
- **1982**: Parameter spaces [Hebert and Ponce, 1982]
- **1983**: Primitives shapes for object recognition [Oshima and Shirai, 1983]
- In this survey: 1998 - 2016
Context

Applications

• **Robotics**: Scene tracking and mapping (SLAM)
• **Modeling**: Lightweight scene reconstruction
• **Shape Processing**: Bounding shapes
• **Rendering**: Level-of-details, occlusion, soft shadowing
• **Interaction**: Navigation space
• **Animation**: Control rigs, Skinning weights
• **Architecture**: Building modeling

[Lee et al., 2012]
[Décoret et al., 2003]
[Furukawa et al., 2009]
[Thiery et al., 2016]
Organization

• Background
• Theoretical Foundations
• Characterization
• Methods and Applications
• Metrics and Evaluation
• Discussion
Background

3D Data Acquisition

real world

color capture

color images

structure from motion

point cloud

depth capture

depth images

registration

reconstruction

mesh

input for primitive detection
Background

Simple Geometric Primitives

- **Limited number** of parameters
- **Convex, Symmetric**
- Basic shape that **can be assembled**
- **Trimmed** shape surfaces
  - Surfaces of objects, not volumes
  - Trimming: convex hull, connected components [Schnabel et al., 2007]
  - Merge patches [Biswas and Veloso, 2011]
  - Compact boundary curve
Theoretical Foundations

Three Categories

- Stochastic
  - RANSAC
  - Local statistics
- Parameter spaces
  - Hough transform
  - Clustering
- Clustering
  - Primitive growing
  - Automatic
  - Segmentation and fitting

[Attene and Patanè, 2010]
Theoretical Foundations

RANSAC [Schnabel et al., 2007]

**Repeat N times**
1. Random minimal set
2. Primitive shape fitting
3. **Shapes scores with all points**
4. Find best primitive
5. If score is high enough
   5.1. Keep primitive
   5.2. Remove inliers

**Optimizations** for speed and quality

⚠️ dominates complexity
Theoretical Foundations

RANSAC

• Pros
  • Simple
  • General
  • Accurate
  • Robust to outliers

• Cons
  • Many parameters to tune
  • Dependent on a minimum set
  • No spatial consistency
  • Not reproducible
Theoretical Foundations

Local Statistics

• Occupancy probabilities
• Infer primitive parameters
• Bounding shapes

[Bagautdinov et al., 2015]

Occupancy Maps [Carr et al., 2012]
Theoretical Foundations

Local Statistics

• Pros
  • Application-specific

• Cons
  • Model-dependent
Theoretical Foundations

Hough Transform

• Shape parameter space
• Discretization, accumulation and vote [Hough, 1962]
• Line and circle detection [Ballard, 1981, Duda and Hart, 1972]
• Many variants for better performance
Theoretical Foundations

Hough Transform: In 3D

- Planes: spherical coordinates
- Cylinders: orientation, then position

Plane Hough space

Cylinder orientation detection

[Rabbani and Van Den Heuvel, 2005]
Theoretical Foundations

Hough Transform

• Pros
  • Handles missing data
  • Supports many model instances
  • Relatively robust to noise

• Cons
  • Unbounded space size
  • Dependent on parameter space quantization
Theoretical Foundations

Clustering Parameter Spaces

- For planes: normal, distance to origin
- Step 1: Gauss sphere clustering
- Step 2: Threshold distance

Normal space clustering [Chen and Chen, 2008]

[Holz et al., 2011]
Clustering Parameter Spaces

• Pros
  • Robust to outliers

• Cons
  • Restricted to low dimensions
Theoretical Foundations

Primitive-driven Region Growing

- Connected component in 2.5D/3D data
- Propagation based on primitive heuristics
- Iterative neighbor merges

Hierarchical point cloud clustering [Attene and Patanè, 2010]

Agglomeration in depth images [Feng et al., 2014]
Theoretical Foundations

Primitive-driven Region Growing

• Pros
  • Meaningful segmentation
  • Spatial consistency

• Cons
  • Slow
  • Local
  • Sensitive to initial conditions (seeds)
  • Sensitive to noise
  • Sensitive to outliers
Theoretical Foundations

Automatic Clustering

- Lloyd clustering: K-Means, Mean Shift
- Iterations of
  - Geometry partitioning (point assignment)
  - Shape fitting in each partition
- Random initialization
- “Variational Shape Approximation”

[Cohen-Steiner et al., 2004]

[Wu and Kobbelt, 2005]
Theoretical Foundations

Automatic Clustering

• Pros
  • No prior on location
  • Few parameters

• Cons
  • Dependent on seeds
  • Sensitive to outliers
  • Can require numerous clusters (K-means)
Theoretical Foundations

Segmentation: Primitive oblivious

- Ignoring primitive shapes
- Region growing, flooding, classification
- Fitting primitives to segments (PCA, Least-Squares, Gradient Descent)

Geometry [Rusu et al., 2009]

Semantics [Verdie et al., 2015]

Rules [Martinovic et al., 2015]
Theoretical Foundations

Segmentation

• Pros
  • Vast literature for segmentation
  • Tailored for application

• Cons
  • Can merge different primitives
  • Application-specific
  • Sensitive to noise
  • Sensitive to outliers
Theoretical Foundations

Assembling Primitives

• Assemble detected shapes
• Bound objects, rooms, buildings
• Generate-and-test strategy

Box candidates [Jiang and Xiao, 2013]

Hierarchical rules [Lin et al., 2013]

[Shen et al., 2011]
Theoretical Foundations

Comparison

- Speed
- Repeatability
- Simplicity
- Generality
- Robustness to outliers
- Robustness to noise
- Robustness to incomplete data
- Meaningful data fidelity
- Scalability
- Scalability
- Generalization
- Segmentation

RANSAC
Hough transform
Primitive growing
Characterization

Characteristics

• Data
• Detected primitives
• Detection Category
• Application context
• 14 properties
Characterization

Application Context

- Individual objects
- Indoor scenes
- Outdoor scenes: urban or natural

[Schnabel et al., 2007] [Zhou et al., 2015] [Rusu et al., 2007] [Goron et al., 2012] [Ochmann et al., 2014] [Ochmann et al., 2016]
Characterization

Properties: Accuracy

• Data Fidelity
• Abstraction Level

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<thead>
<tr>
<th>Value</th>
<th>Characteristics</th>
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<tbody>
<tr>
<td>1</td>
<td>Approximating planes or bounding boxes</td>
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<td>2</td>
<td>Planes fitting planar data only</td>
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<td>3</td>
<td>Planes and primitives fitting all data</td>
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Data fidelity scale

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<th>Level</th>
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<td>Raw point cloud</td>
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<td>Assembled primitives</td>
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Abstraction scale
Characterization

Properties: Practicality

- Timing: online / offline
- Scalability
- Intuitive Tuning

Controlling abstraction in Sphere-Meshes [Thiery et al., 2013]
Characterization

Properties: Practicality

- User Assistance

Manual fitting in O-Snap [Arikan et al., 2013]

User interaction in 3-Sweep [Chen et al., 2013]

User strokes to fix segmentation [Shao et al., 2012]
Characterization

Properties: Practicality

• Learning Phase

Facade labeling [Martinovic et al., 2015]

Database model matching [Shao et al., 2012]
Characterization

Properties: Practicality

- Temporal Consistency

Ray casting depth and ID maps

Extended planes and rasterized ID map

Existing planes

New planes

Planes in pose graph [Kaess, 2015]

Plane tracking [Zhang et al., 2015]
Characterization

Properties: Information

- Semantics
- Needs Extra Information
- Provides Meta Data

Relations between rooms
[Ochmann et al., 2014]

Semantics
[Golovinskiy et al., 2009]
Characterization

Properties: Robustness

- Noise
- Outliers
- Incomplete Data

RANSAC [Schnabel et al., 2007]

Completion in O-Snap [Arikan et al., 2013]
## Methods and Applications

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Methods and Applications

Web Application: Sort, Visual compendium, Links to methods, code and datasets

https://perso.telecom-paristech.fr/boubek/papers/GeoPrimFitSurvey/
Methods and Applications

Survey

• 73 references from 1998 to 2016
• Communities: Graphics, Robotics, Vision, Image Processing
• Sorted by detected shapes
• Then by application context
• Grouped by theoretical foundation
Methods and Applications

Planes: Indoor Scenes

- Region growing with planar heuristics
  - Unorganized 3D point clouds
  - Image structure: faster search for neighbors [Feng et al., 2014]
  - Slower than stochastic, but high quality, consistent
  - Sensitive to noise, but lower than outdoors

Plane matching and registration [Salas-Moreno et al., 2014]
Joint segmentation [Mattausch et al., 2014]
Regularized model [Monszpart et al., 2015]
CAD model matching [Shao et al., 2012]
Methods and Applications

Planes: Indoor Scenes

- RANSAC
  - Fast (for robotics)
  - Less consistent and accurate
  - Can be refined with time

Planar SLAM
[Kaess, 2015]

Spatial relations
[Ochmann et al., 2014]

Floor plans
[Ochmann et al., 2016]

CAD models
[Chen et al., 2014]
Methods and Applications

Planes: Indoor Scenes

• Parameter space
  • Hough transform for "Manhattan" scenes [Limberger and Oliveira, 2015]
  • Only a few directions, stable
  • Simpler clustering of param space [Holz et al., 2011]
Methods and Applications

Planes: Indoor Scenes

- Segmentation
  - Watershed on range data [Whitaker et al., 1999]
  - Manual plane matching for registration

[Whitaker et al., 1999]
Methods and Applications

Planes: Outdoor Scenes

- Primitive growing
  - House models
  - Semantic labeling and plane assembly
  - Assembling is robust to missing data
  - Recover full house structure
  - Outdoor objects far from each other

[Lin et al., 2013]
Methods and Applications

Planes: Outdoor Scenes

- Parameter space
  - Urban scene reconstruction
  - Normal-based clustering
  - Plane clipping
  - Buildings with regular planar parts

[Chen and Chen, 2008]
Methods and Applications

Planes: Outdoor Scenes

• RANSAC
  • House and building modeling
  • Planes intersections
  • RANSAC can miss planes → incomplete model

Interactive completion
[Arikan et al., 2013]

[Interactive completion]

[Hybrid model]

[Lafarge and Alliez, 2013]
Methods and Applications

Planes: Outdoor Scenes

• Hough transform
  • 3D models of buildings
  • Pre-segmentation with ground plans
  • Per-segment fitting
  • Followed by region growing

[Vosselman and Dijkman, 2001]
Methods and Applications

Planes: Individual Objects

• Hough transform
  • Simplified visualization of meshes
  • Billboard Clouds
  • Render few planar proxies

Original model (14K triangles) vs 20 billboards
[Décoret et al., 2003]
Methods and Applications

Planes: Individual Objects

- Automatic clustering
  - Variational Shape Approximation
  - K-means on polygonal mesh
  - Accurate, consistent results
  - Requires fixed number of patches

62K triangles to 110 planar patches
[Cohen-Steiner et al., 2004]
Methods and Applications

Bounding Boxes and Cuboids: Indoor Scenes

• Stochastic
  • Person identification from depth maps
  • Local statistics on floor
  • Robust to occlusions

[Bagautdinov et al., 2015]
Methods and Applications

Bounding Boxes and Cuboids: Indoor Scenes

- Assembled planes
  - Boxes around objects
  - Candidate generation and activation
  - Robust to missing faces

[Jiang and Xiao, 2013]  [Khan et al., 2015]
Methods and Applications

Bounding Boxes and Cuboids: Outdoor Scenes

• Stochastic
  • Detect vehicles and pedestrians
  • Occupancy maps on floor
  • Specific to application, sensitive to data

[Carr et al., 2012]
Methods and Applications

Bounding Boxes and Cuboids: Outdoor Scenes

- Segmentation
  - Facade splitting
  - Fit boxes to semantic components
  - Architectural priors, regular facades
  - Meaningful representation

Assembling planes
[Shen et al., 2011]

Semantic labeling
[Martinovic et al., 2015]
Methods and Applications

Bounding Boxes and Cuboids: Individual Objects

- Assembled planes
  - 3D shape templates
  - Cuboids from grown planar patches
  - Consistent across object instances
  - Deformation of template parts

[Kim et al., 2013]
Methods and Applications

Spheres, Cylinders, Cones: Indoor Scenes

- Hough transform
  - Cylinder parameter space
  - Industrial setups
  - Robust to occluded parts
  - Match cylinders and register views [Rabbani et al., 2007]

[Rabbani and Van Den Heuvel, 2005]
Methods and Applications

Spheres, Cylinders, Cones: Indoor Scenes

- Segmentation
  - Identify objects on table
  - Simple model for household robots
  - Connected components in 2D table space
  - Hybrid model for accuracy

[Goron et al., 2012]
Methods and Applications

Spheres, Cylinders, Cones: Outdoor Scenes

- Segmentation
  - Classify natural elements / buildings
  - Fit cylinders for trees, cables, columns / spheres for domes
  - Semantic interpretation

Robot in natural environment [Lalonde et al., 2006]

City modeling [Lafarge and Mallet, 2012]
Methods and Applications

Spheres, Cylinders, Cones: Outdoor Scenes

• RANSAC
  • High level model of buildings
  • Hierarchical assembly, decomposition
  • Genericity of RANSAC for revolution shapes

[Chen et al., 2011]
Methods and Applications

Spheres, Cylinders, Cones: Outdoor Scenes

- User assisted
  - Aerial images
  - Select primitive type, approximate fit
  - Auto refined

[Wang and Tseng, 2004]
Methods and Applications

Spheres, Cylinders, Cones: Individual Objects

- Primitive growing
  - Object parts, meaningful segmentation
  - Separated by geometric heuristics

Mechanical parts [Attene and Patanè, 2010]
Sphere mesh [Thiery et al., 2013]
Generalized cylinder [Zhou et al., 2015]
Methods and Applications

Spheres, Cylinders, Cones: Individual Objects

- Automatic clustering
  - Clusters naturally separate parts
  - Iterations of triangle assignment, primitive fitting
  - Extending VSA to more complex, fewer shapes

Hybrid VSA
[Wu and Kobbelt, 2005]

Quadric fitting
[Yan et al., 2012]
Methods and Applications

Spheres, Cylinders, Cones: Individual Objects

- RANSAC
  - Mechanical models
  - Need connected component

Regularization with Globfit
[Li et al., 2011]

[Schnabel et al., 2007]
Methods and Applications

Spheres, Cylinders, Cones: Individual Objects

• Interactive methods
  • Single RGB view: 3-Sweep
  • Draw strokes, auto snapped to edges
  • Stroke semantics
  • Regular models but no automation

Geo-semantic strokes [Shtof et al., 2013]

3-Sweep [Chen et al., 2013]
Methods and Applications

Ellipsoids, Tori, Parallelepipeds: Outdoor Scenes

- Segmentation
  - Bounding ellipsoids for organic objects, vegetation
  - Parallelepipeds for building superstructures
  - Usually no clear boundary

Natural elements [Lalonde et al., 2006]

Urban elements [Verdie et al., 2015]
Methods and Applications

Ellipsoids, Tori, Parallelepipeds: Individual Objects

- Automatic clustering
  - Fit ellipse patches to organic shapes
  - Far from input but meaningful
  - Light modeling of complex shapes

Ellipse VSA
[Simari and Singh, 2005]
Methods and Applications

Ellipsoids, Tori, Parallelepipeds: Individual Objects

- Tori
  - Industrial environments and objects

Parts of objects, elbows [Rabbani et al., 2007]

Blends between parts [Attene and Patanè, 2010]
Evaluation Metrics

- **Sum of Squared Differences (SSD)**
  For primitives $S_i, i \in [0, N]$ gathering inliers $P^i_j, j \in [0, M]$, the fitting error is
  \[
  \epsilon = \sum_{i=0}^{N} \sum_{j=0}^{M} \left\| P^i_j - \text{proj}(P^i_j, S_i) \right\|^2
  \]
  where \( \text{proj}(P^i_j, S_i) \) is the projection, i.e. closest point, of point $P^i_j$ on its shape $S_i$

- **Hausdorff distance**
  For two sets of points $a \in A$ and $b \in B$,
  \[
  H_{AB} = \max_{a \in A} \{ \min_{b \in B} d(a, b) \} \]
Metrics and Evaluation

Processing Metrics

• Quadric Error Metric (QEM) [Garland and Heckbert, 1997]
  For a vertex \( v \) and \( N \) planes \( P_i, i \in [1, N] \) with normals \( p_i, i \in [1, N] \):
  \[
  \epsilon = \sum_{i=1}^{N} \text{dist}(v, p_i)^2 = \sum_{i=1}^{N} (p_i^T v)^2 = v^T (\sum_{i=1}^{N} p_i p_i^T) v = v^T Q v
  \]

• Spherical Quadric Error Metric (SQEM) [Thiery et al., 2013]

Distance from a sphere to oriented planes
[Thiery et al., 2013]
Metrics and Evaluation

Reproducibility: Online publication of

- Implementation (19 papers)
- Labeled datasets (11 papers)

NYU Depth Dataset V2 [Silberman et al., 2012]
Discussion

Concluding Remarks

• Simple geometric shapes as **building blocks**
• **Simplified tool** for 3D data analysis
• **Faster and accurate** processing
• Multiple **detection paradigms**
• Application-oriented **classification**
Discussion

Spatial Reasoning

• Enrich data through **structural information**
• Qualitative and quantitative **knowledge of spatial locations**
• Graph of **geometric relations**
• Hierarchical **adjacency**
• Room **connectivity**
• But: only post-detection

GlobFit [Li et al., 2011]

[Ochmann et al., 2014]

[Silberman et al., 2012]
Discussion

Research Challenges: Model

- Completeness
- Consistency

Plane extrapolation from 3D Lite (5h per scene)  
[Huang et al., 2017]

Dense Planar SLAM  
[Salas-Moreno et al., 2014]
Research Challenges: Interpretation

- Semantics
- Functional behavior, Constraints, Visibility
- Parametric primitives

Generalized Cylinder [Zhou et al., 2015]

3-Sweep [Chen et al., 2013]
Discussion

Research Challenges: Processing

- **Parallel** execution [Oesau et al., 2016]
- **Compressed** representations
- Primitives for **capture**
- **Multiscale**

Model hierarchy
[Attene and Patanè, 2010]
Discussion

Research Challenges: Deep Learning

- **Detect** primitives
- Primitives as **features**
- Geometry of DNN

Supervised Fitting (based on PointNet++)
[Li et al., 2019]
A Survey of Simple Geometric Primitives Detection Methods for Captured 3D Data

Adrien Kaiser, Jose Alonso Ybanez Zepeda, Tamy Boubekeur

https://perso.telecom-paristech.fr/boubek/papers/GeoPrimFitSurvey/
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