Completion and Reconstruction with Primitive Shapes

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Introduction

- Acquisition
  - Tedious
  - Time consuming
  - Incomplete

- Final model
  - Complete
  - plausible
Introduction

• Man-made environment
  – Primitive shapes
    • Planes
    • Spheres
    • Cylinders
    • ...

• Useable for completion?
Introduction

• What can we reconstruct from this?
Primitive guided completion

• Extend detected primitives such that
  – Closed surface is created
  – Sharp features are extended and inferred

• Allows idealized reconstruction
  – Recover exact primitives
  – Ignore noise or surface detail
Primitive guided completion

- Difficulties
  - Inexact primitives
  - Missing primitives
  - Holes with multiple boundaries
  - Ambiguities
Primitive guided completion

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Primitive guided completion

• Variational approach
  – Novel energy functional incorporating primitives’ guidance
  – Arbitrary number of primitives
  – Arbitrarily complex intersections
  – Arbitrary number of hole boundaries
  – Plausible results for inexact/missing primitives

• Can create idealized reconstruction
  – Recovers sharp features
  – Robust to noise and outliers

• Can also reconstruct detailed geometry
  – Handle surface parts not approximated by primitives
Previous work

• Reverse engineering
  – Extensive use of primitives
  – Completion of small holes within a primitive

• Surface reconstruction
  – e.g. Curless, Levoy 96 Space Carving
    • Plausible only in relatively small holes, no structure propagation

• Surface completion
  – PDE based, energy minimization
    • smooth fillings suitable for small holes (no sharp features)
  – Example based
    • Needs fitting examples (requires large database)

• Range images
  – Fisher et al.: Completion involving at most two primitives per hole
Previous work

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Will not talk about primitive detection!
**Primitive Detection**

- **Finds on point-cloud** $P$
  - Set of **oriented** primitives
  - Subsets associated with a primitive (**support**)
  - Subset of remaining points

  $$P = S_1 \cup \ldots \cup S_A \cup R$$

- **RANSAC approach** [Schnabel et al 07]
  - planes, spheres, cylinders, cones, tori
  - Other methods possible
Variational Approach

- Sought: Minimal surface
- Intuition: Modify surface area
  - Cheap when on primitive
  - Expensive otherwise
- Reconstruction via energy minimization
  - Similar to Hornung and Kobbelt 06, Lempitsky and Boykov 07
Variational Approach

- Sought: Minimal surface
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- Reconstruction via energy minimization
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- Constraint: Reconstructed support of primitives must be connected
Primitive adherence

- Modified surface area
- Energy of surface $S$ consists of three terms:

\[ E(S) = E_a(S) - E_p(S) + E_c(S) \]

- $E_a(S)$ measures Surface area
- $E_p(S)$ measures primitive adherence
- $E_c(S)$ enforces inside/outside constraints
Primitive adherence

- Energy of surface $S$ consists of three terms:

$$E(S) = E_a(S) - E_p(S) + E_c(S)$$

$$= \int_S dA - \int_S \mathbf{H}(\langle n | v \rangle) dA + E_c(S)$$

$n$ Surface normal of $S$

$v : \mathbb{R}^3 \rightarrow \mathbb{R}^3$ Vector field of primitives' normals (defined only on primitives)

$\mathbf{H}(x) := \begin{cases} 
1 & x > 0 \\
0 & \text{otherwise}
\end{cases}$
**Primitive adherence**

\[ E(S) = E_a(S) - E_p(S) + E_c(S) \]

\[ = \int_S dA - \int_S H(\langle n|v\rangle) dA + E_c(S) \]

\[ n \quad \text{Surface normal of } S \]

\[ v : \mathbb{R}^3 \rightarrow \mathbb{R}^3 \quad \text{Vector field of primitives' normals (defined only on primitives)} \]

\[ H(x) := \begin{cases} 
1 & x > 0 \\
0 & \text{otherwise}
\end{cases} \]
Constraints

• Third term enforces inside/outside

\[ E(S) = E_a(S) - E_p(S) + E_c(S) \]

\[ E_c(S) = \int_{C_{in} \setminus S_{in}} \lambda dV + \int_{C_{out} \setminus S_{out}} \lambda dV \]

• Placement of constraints discussed later
Discretization

- Problem: Energy has many local minima
- Find discrete globally optimal solution with graph-cut
- For now: ignore connectivity constraint
- Define discrete edge cost on volumetric grid
Discretization

- Problem: Energy has **many local minima**
- Find **discrete globally optimal** solution with graph-cut
- For now: ignore connectivity constraint
- Define discrete edge cost on volumetric grid

\[
\hat{E} = \hat{E}_a - \hat{E}_p + \hat{E}_c
\]
Discretization

\[ \hat{E} = \hat{E}_a - \hat{E}_p + \hat{E}_c \]

- \( \hat{E}_a \): Mimic surface area (after Boykov and Kolmogorov 2003)
- \( \hat{E}_p(e) := \begin{cases} \hat{E}_a(e) & \text{a } P_i \text{ intersects } e \text{ and } \langle n_{P_i} | e \rangle > 0 \\ 0 & \text{otherwise} \end{cases} \)
- \( \hat{E}_c \): Responsible for constraints
Discretization

\[ \hat{E}_c \] Places constraints at endpoints of edges cut by primitives' support

\[ \hat{E} = \hat{E}_a - \hat{E}_p + \hat{E}_c \]
Connectivity

• Up to now: Disregarded connectivity
Connectivity

- Each cut-edge is representative for local surface patch
- Cut-edges intersected by primitive must be connected
  - Must form **connected superset of original support**
- Cannot be found with single graph-cut
- Instead: Simple but effective greedy approach
Connectivity

• Each cut-edge is representative for local surface patch
• Cut-edges intersected by primitive must be connected
  – Must form **connected superset of original support**

• Iterate:
  – Compute reconstruction with graph-cut
  – Detect violations of connectivity constraint with graph traversal
    • Traversal originates in original support of primitive
  – Increase cost of violating edges
Surface extraction

- Using Kobbelt et al.’s [2001] Extended Marching Cubes
- Use primitives‘ normals and intersections at cut-edges

- Close to primitive transitions:
  - cut-edges intersected by multiple primitives
  - Which normal/intersection to pick?
Surface extraction

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  - Which normal/intersection to pick?

- Disambiguation
  - Multi-label MRF on cut-edges
Surface extraction
Detail reconstruction

- Completion with primitives is now possible
- Reconstruction adheres to primitives everywhere
Detail reconstruction

• Completion with primitives is now possible
• Reconstruction adheres to primitives everywhere
• How to handle detail?
Detail reconstruction

- Based on a approach by Lempitsky and Boykov [2007]
- Derive vector field $u$ from input points

- New energy:

\[ E(S) = E_a(S) - E_p(S) - \lambda E_u(S) \]

\[ E_u(S) = \int_S \langle n | u \rangle dA = \int_{S_{in}} \text{div}(u) dV \]

- Minimum can also be found with graph-cut
Detail reconstruction

- Holes are still filled with primitives!
Results

Jia et al. [2007]
Results

38 primitives, approx. 2 min

Lempitsky and Boykov [2007]
Results

51 primitives, approx. 8 min
Results

171 primitives, approx. 9 min
Results
Conclusion

- Presented novel primitive guided reconstruction
  - Automatically completes holes by extending primitives
  - Plausibly resolves ambiguities
  - Reconstructions and extends sharp features
  - Infers sharp features in holes from primitive intersections
  - Can generate idealized or detailed model

- In the future
  - Other primitives could be possible (NURBS, database, ...)
  - Refit primitives
  - Extend to exploit (self-)similarity and regularity
  - Synthesize detail/color on extended primitives
Thank you!

• Some holes are not to be filled...