A Volumetric Method for Building Complex Models from Range Images
Contribution

Given a set of aligned, dense range images, provides a manifold closely approximating the original model with several *desirable properties*
Desirable Properties

- Representation of range uncertainty
- Utilization of all input data
- Incremental, order-independent updating
- Water-tight reconstruction
- Robust
- Efficient performance
- No restriction on model topology
Overview

• Given set of range images: \( R_1, R_2, \ldots, R_{N-1}, R_N \)
• Create signed distance functions: 
  \( d_1(x), d_2(x), \ldots, d_{N-1}(x), d_N(x) \)
• Compute the cumulative distance function \( D(x) \) from these functions
• Extract the manifold as the isosurface \( D(x) = 0 \)
Generating $d(x) \rightarrow$ Computing $D(x)$
Computing $D(x)$
Computing D(x)

- Distance functions: $d_1(x), d_2(x), \ldots, d_{N-1}(x), d_N(x)$
  - Generated by following line of sight from sensor to reconstructed range surface
- Weights: $w_1(x), w_2(x), \ldots, w_{N-1}(x), w_N(x)$
  Measure of certainty of correctness of range estimate
  - $w_i(x) = \text{Dot}(\text{vertex normal, line of sight})$
  - Adjusted to taper off as distance from the line of sight increases
Computing $D(x)$
Computing $D(x)$

- Computation
  
  $$W(x) = \sum w_i(x), \quad D(x) = \frac{\sum d_i(x)w_i(x)}{\sum w_i(x)}$$

- Can be performed incrementally, orderlessly
  
  $$W_i(x) = W_{i-1}(x) + w_i(x)$$
  $$D(x) = \frac{d_i(x)w_i(x) + D_{i-1}(x)}{w_i(x) + W_{i-1}(x)}$$
Computing $D(x)$
Computing $D(x)$

- $d_1$
- $d_2$
- $D$

- $w_1$
- $w_2$
- $W$

- $D_{\text{max}}$
- $D_{\text{min}}$

- Isosurface

- Sensor
Algorithm So Far

• Set all voxel weights to zero
• For each range image $R_i$
  – Obtain its triangle mesh
    • Weight = dot(vertex normal, line of sight) at each sample vertex
    • Signed distance at each voxel
Determining distance contribution
Algorithm So Far

• Set all voxel weights to zero

• For each range image $R_i$
  – Obtain its triangle mesh
    • Sample vertex weight = $\text{dot}(\text{vertex normal, line of sight})$
    • At each voxel
      – Signed distance = distance along viewing ray from voxel to range surface
      – Weight = interpolation of vertex weights of triangle intersected by viewing ray
  – Compute $D(x)$ as described
  – Isosurface extraction: $D(x) = 0$
    • Ignore remaining zero weight, i.e. unseen regions
Hole filling

• Unseen portions of the surface appear as holes in the current reconstruction

• Direct filling in polygonal model
  – Does not use all available information
  – Difficult to obtain robust result

• Solution provided: *Space carving*
Algorithm with Space Carving

• Initialize all voxels to the “unseen” state
• Update near range surface voxel distance and weight values as before
• Space carving:
  – Follow the lines of sight back from the observed surface
  – Mark the corresponding voxels as “empty”
• Isosurface extraction: $D(x) = 0$
• Fill holes: Create a surface between regions marked “empty” and regions marked “unseen”
Algorithm with Space Carving

- Unseen
- Hole fill isosurface
- Observed isosurface
- Near surface
- Empty

Sensor

\[
\begin{align*}
D(x) &= D_{\text{max}} \\
W(x) &= 0
\end{align*}
\]

\[
\begin{align*}
D(x) &= D_{\text{min}} \\
W(x) &= 0
\end{align*}
\]

\[
\begin{align*}
D_{\text{min}} &< D(x) < D_{\text{max}} \\
W(x) &> 0
\end{align*}
\]
Implementation and Usage

• Software optimizations
  – Run-length encoded data structures
  – Memory coherent traversal
  – Binary depth trees
  – Restricted Marching cubes

• Typical data size
  – 60 scans
  – 10 million input vertices
  – 100 million voxels
Results: Robustness

Merging ranged images of a 1.6mm drill bit from 12 orientations at a 30 degree spacing
(a) Unorganized points
(b) Wire frame tessellations
(c) Slice generated by polygonal method
(d) Slice generated by volumetric method
Results: Robustness

- Polygonal method rendering
- Volumetric method rendering
- Original drill bit
Results: Hole filling

(a) Original image with hole
(b) Image after hole filling
(c) Close-up of the hole
(d) Close-up of the filled hole
Results: Hole filling
Results: Detail achieved
Limitations

• Scanning
  – Accessing all surface points is challenging
  – Reflectance affects results

• Volumetric method
  – Thin surfaces
  – Sharp corners
Possible Extensions

• Improving execution time of space carving algorithm
• Large-scale scenes