Enhanced Pre-Conditioning Algorithm for the Accurate Alignment of 3D Range Scans

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Overview

- 3D Model Construction
- Related Work in Range Scan Alignment
- Scanning Device and Process
- Semi-Automated Data Filtering
- 2-Phase Range Scan Alignment
  - Initial Estimate Alignment
  - Refined Bounding Volume Assisted Scan Alignment
- Alignment Evaluation
What are we trying to accomplish?

- **3D Model Construction**
  - Time of Flight (TOF) Laser-based distance measuring device
    - Exterior environment
    - No control of scanning conditions (sunlight, weather, etc).
  - Long-range (100-200[m]), low-resolution (10k) range images
    - Large exterior structures can be captured (vehicles, buildings, etc.)
  - Accurate pairwise range scan alignment
  - Minimize required range scan count
    - Scanning in the field has several associated costs (time, obstacles, etc.)
Related Work

- **Range Scan Alignment**
  - Registration of 3-D Shapes [Besl. et al. 1992]
  - ICP Accuracy Improvements [Chen, Medioni. 1992]
  - ICP: Efficient Variants [Rusinkiewicz, Levoy. 2001]
    - Modularization of selection, matching, weighting, etc.
  - Relevant Point Sampling [Torsello et al. 2011]
    - Selects interesting curvatures; yet computationally expensive

- **Range Scan 3D Object Construction**
  - Automated multi-view quadruple alignment of unordered range scans [ter Harr, et al. 2007]
    - Considers a large numbers of scans; but not all scans are aligned properly – a severe implication when considering only 4 scans
  - 3D Model Pipeline (Kinect) [Chatterjee, et al; 2012]
    - Utilizes a high number of scans and range image filtering
Why existing alignment techniques won’t work

- Previous Research Assumptions
  - Utilize highly accurate data-sample collection devices
    - Surface accurately represented
    - Easily identifiable outliers (or pre-cleaned datasets)
  - Significant pairwise scan overlap
    - Require a large number of scans
    - Assume scans are acquired in controlled environments
  - Alignment convergence is not required for each scan pair
Research Aim

- **Research Intent**
  - Facilitate data collection through hardware prototype
  - Limit the number of required range scans
  - Provide semi-automated data filtering techniques
  - Rotation-based range scan initial alignment
  - Bounding volume assisted Iterative Closest Point (ICP) alignment

- **Newly Acquired Considerations**
  - Material Properties of scanned object (metallic surfaces)
  - Transparencies in the scanned object (windows)
  - Sunlight interference
  - Erratic, valid data samples
Scanning Device and Process

- TOF Laser-based Distance Measuring Device Prototype
  - Each scan is composed of \((m \times n)\) depth samples from position \(P\)
  - Scanner direction defined by \((\theta, \phi)\); the pan and tilt angles of the device
  - Each distance sample is converted to a 3D point representing a point on the object's surface
Scanning Procedure
- $k$-Scans are performed circularly around the focus object $F$
- Each scan $P_i$ has an associated angle where $(0 \leq \text{angle} \leq 360)$
- Positions might be limited by obstacles
- Distances (scanner to object) and scanner elevation are not constant
Automated Filtering and Painting

- TOF Device Scan Data Collection
  - Contains a large amount of background information
  - Valid and invalid data-points are not easily distinguishable
  - Surface material properties directly tied to data accuracy
  - Transparencies provide invalid surface information

- Automated Filtering
  - Constrain scanner parameters ($\theta$, $\varphi$)
  - Distance
  - Signal Strength

- Manual Data Elimination (Painting)
  - Highly accurate removal of data-points via radial selection
  - Mouse gestures represent brush strokes to remove invalid data-points
  - Allows for removal of invalid points from interference and transparency
TOF Device Raw Data (Legacy Dataset)

Subaru Legacy Scan Data (340 pan points, 80 tilt points – 27,200 Points)
Automated Filter Result (Legacy Dataset)

Subaru Legacy Scan Data – After Automated Filters are Applied
Manual Painting (Legacy Dataset)

Subaru Legacy Scan Data – Painting Example
Manual Data Removal Result (Legacy Dataset)

Subaru Legacy Scan Data – Example point-cloud used for alignment (11,965 points)
2-Phase Scan Alignment

- Initial Estimate Scan Alignment
  - Estimates Pairwise Alignments (provides approximate alignment)

- Refined Scan Alignment
  - Refined Bounding Volume Assisted ICP Alignment
Initial Estimate Scan Alignment

- **Axis-Aligned Bounding Box (AABB) Translational Alignment**
  - Considers (clean) scans with associated angles
  - Pairwise comparison of angles determines AABB shift direction
  - Tries to approximate surface correspondence (requires outlier removal)
  - Rotation has been applied about the Y axis (images below illustrate a top view of two scan surfaces)

Two scans with angles theta and phi

Scan surfaces with AABBs (as seen from above)

AABBs of the two scans have been aligned
Initial Estimate Alignment (Application)

Two Legacy scans (0 and 90[deg])
Top View
(Pre-AABB-Alignment)

Two Legacy scans (0 and 90[deg])
Top View
(Post-AABB-Alignment)
Initial alignment between 4 edited range scans (Legacy Dataset)
Refined Bounding Volume Assisted ICP

- **Development Intent**
  - Discards points with no correspondence between scan pairs
  - Ensures ICP will perform well on erratic data samples (with appropriate initial alignment)
  - Reduces required number of scans (minimizes required overlap)
  - ICP has a better chance for convergence when utilizing point sets with a higher number of correspondences

- **Algorithm**
  - Execute Initial Alignment
  - Utilize bounding volumes to identify intersect region
  - Only points within the intersection are considered for ICP
  - Align using any ICP algorithm with established improvements
Bounding Volume (AABB) Overlap Intersections

Scan-Pairs: **Bunny** (left), **Chair** (center), and **Legacy** (right)

The intersection volume is illustrated in the bottom row
ICP algorithm executed on (Red/Green) points
Experimental Evaluation

- Alignment Evaluation
  - Iterations to Convergence (Pairwise-ICP)
  - Quality based on Root-Mean-Square-Deviation (RMSD)
  - Number of scans and overlap percentage
  - Utilizing the Scanalyze ICP algorithm\(^6\)
    - Sampling Rate: 20%
    - Uniform Norm-Space Sampling
    - Minimization: Point-to-Plane\(^7\)
    - Iterations: 10
Experimental Evaluation (Cont’d)

- ICP [vs] Bounding Volume Assisted ICP Convergence over 10 Iterations

  - Subaru Legacy Dataset Alignment Result (Scans 180°-270°; a 90° Separation)

![](chart.png)
ICP [vs] Bounding Volume Assisted ICP Decrease in RMSD

- RMSD decreases drastically when using our method with 4 scans

Scan-Pairs (Avg. Decrease in RMSD – Legacy: ~70%, Bunny: ~40%)
Alignment Results (Legacy Dataset)

Legacy: Bounding Volume Assisted ICP Alignment (4 Scans)
Alignment Results (Legacy Dataset)

Legacy: Bounding Volume Assisted ICP Alignment (4 Scans)
Alignment Results (Cont’d)

Bounding Volume Assisted ICP Alignment Results (3 scan sets)

Stanford Bunny Alignment Result (4 Range Scans)
Chair Alignment Result (8 Range Scans)
Virtual Truck Alignment Result (8 Range Scans)
Conclusion

- Facilitate effective data collection from Laser-Based TOF devices
  - Surface materials and transparent objects present erratic data
- Semi-Automated Filtering
  - Eliminate unavoidable sample errors
  - Technique allows for precision data elimination
- Introduced an efficient method for initial alignment
  - Accurate alignment technique for TOF devices
  - Computationally Inexpensive (2x-AABB, transformation calculation)
Conclusion (Cont’d)

- **Bounding Volume Assisted ICP Alignment**
  - Decreased RMSD (for scan sets of 8 and 4)
  - Reduced Iterations for convergence
  - Accuracy is greatly increased for scan sets with minimal coverage
  - Reduced the number of required scans for a convergence from ICP
  - Reduces costs associated with acquiring numerous scans