A Volumetric Method for Building Complex Models from Range Images

1. Briefly summarize the paper's contributions. Does it address a new problem? Does it present a new approach? Does it show new types of results?

- **[AS]**
  This paper presents a new approach to the problem of reconstructing surfaces from groups of aligned range images. It endorses the idea of making little assumptions about the data, i.e., using all information available, including errors, from range scanners. It produces extremely detailed and high quality reconstructions.
- **[DS]**
  The paper presents a volumetric algorithm for integrating range images. The algorithm has the following desired properties that other algorithms only have a subset of. The properties are (1) representation of range uncertainty, (2) utilization of all range data, (3) incremental and order independent updating, (4) time and space efficiency, (5) robustness, (6) no restrictions on topological type, (7) ability to fill holes in the reconstruction.
  This method was one of the first to produce high quality surfaces by using a very large number of sample points.
- **[FP]**
  This paper introduces progressive surface reconstruction from several range images. Different to previous approaches, this method does not assume that all sampled data is known at an initial stage. Instead, it uses a streaming model to introduce and update sampling information in an order independent way. Structural information provided by the acquisition device is used as fundamental criteria to measure the certainty of the acquired data and its weight in the final reconstruction. The size of the input data and the output triangle meshes are some orders of magnitude larger than in previous results. Therefore, they exhibit reconstruction of more complex models such as Buddha and Dragon.
- **[JD]**
- **[LF]**
- **[MK]**
  This paper proposes an approach to surface reconstruction that seeks to incorporate, to as large extent as possible, the properties of 3D scanners used to acquire 3D data. For example, the authors explicitly to try to take advantage of properties like the regular grid structure of the scanner and the line of sight to the camera in their reconstruction process.
  As a result, the paper is the first to propose an approach that reconstructs a surface that not only leverages information about which points were seen, but also how they were seen.
  Finally, the approach shares traits with the later proposed MPU method in that reconstruction is done locally (per range image) and then glued together with a weighting function to obtain a global implicit function.

2. What is the key insight of the paper? (in 1-2 sentences)

- **[AS]**
  Using all the information available for a given data set and producing specific solutions, rather than general solutions, gives high quality results. In addition, using information about the free space around the data also allows for the improvement of the generated surface by allowing the algorithm to fill holes in the surface in an intelligent way.

- **[DS]**
  The method uses a cumulative weighted signed distance function, then it extracts an isosurface from the volumetric grid. It can then fill in gaps in the surface.
- **[FP]**
  An efficient integration of progressive sampling information is done by defining a signed function on a voxel grid. Results are improved by taking advantage of acquisition device properties.
- **[JD]**
- **[LF]**
- **[MK]**
  One of the key insights of the paper is that if we are given both a surface sample position and the camera position from which it was seen, we know not only that the sample should be on/near the reconstruction but also that nothing else on the line segment should be.

3. What are the limitations of the method? Assumptions on the input? Lack of robustness? Demonstrated on practical data?

- **[AS]**
  This method has difficulty reconstructing sharp corners and thin surfaces.
- **[DS]**
  The method makes a set of assumptions that guarantees that the extracted isosurface is optimal in a least squares sense.
  The isosurface might contain artifacts, which can be eliminated by prefiltering the transition region unseen and empty voxels.
  The method has difficulty bridging sharp corners if no scan spans both surfaces meeting at the corner.
  There is a lower limit to the thickness of the surface that can be reconstructed. This can produce artifacts such as thickening of the surface and rounding of sharp corners.
  Limitations arise from the scanning technology: internal cavities are not seen, difficulty with really complex object, the object's surface properties might affect the scans.
- **[FP]**
  The assumptions on the structural information of the sampled data restrict the method to input sets acquired by just certain types of devices. The authors identify two special types of limitations: algorithmic limitations and technology limitations. On the algorithmic side they found difficulties at reconstruction of sharp corners and thin surfaces. On the technology side the acquisition process (which is done with an optical sensor) is limited to exterior surfaces (does not sample interior surfaces) and may require lot of range images to cover the complete object. The reflectance properties of the surface also affect the accuracy of range registration. Some of these limitations on the acquisition phase are compensated with the hole filling method proposed by the authors.
- **[JD]**
- **[LF]**
- **[MK]**
  One limitation of the method is that is assumes that the surface sheets are well-separated. Specifically, it assumes the existence of a global radius parameter dictating the size of the blending region (and determined by the uncertainty of the measuring device).

4. Are there any guarantees on the output? (Is it manifold? does it have boundaries?)

- **[AS]**
  The output of this method is guaranteed to possess all of the following properties: representation of range or directional uncertainty, utilization of all range data (including error), incremental and order independent updating, time and space efficiency, robustness in the presence of outliers, no restriction on the topological type, and the ability to fill holes in the reconstruction.
- **[DS]**
  A manifold without holes is generated ("under certain assumptions").
- **[FP]**
  Since the reconstruction process is done using marching cubes (on the signed distance function) it is guaranteed that the output is manifold. The hole filling process guarantees a watertight mesh. The marching cube algorithm may generate boundary edges at transition from distance defined voxels to distance undefined voxels.
- **[JD]**
- **[LF]**
- **[MK]**
  The surface is obtained by applying marching cubes to samples of the blended function. As such, the output is guaranteed to be a water-tight manifold.
  The authors propose a neat trick for filling holes: They initialize space with “unseen” values, (equivalent to being deep inside the surface), they fit the implicit function around the scanned points, and then carve out the remaining points on the line segment of sight with “empty” values (equivalent to being far outside the surface). The resulting function is discontinuous near holes, but marching cubes still produces a well-defined surface (similar to Hoppe et al. ’92).

5. What is the space/time complexity of the approach?

- **[AS]**
  The time complexity of this approach, excluding space carving, is O(n), where n is the number of points in the final point cloud. Space carving is slower, however, it is not optimized. The space complexity of this approach is also linear.
- **[DS]**
  Dependent on the resolution of the scan images and the corresponding voxel grid. Parallelization of the algorithm to be proven.
- **[FP]**
  The total storage and time complexity is linear in the number of voxels used in the object model (n) and the number of range images (k) (i.e., registration is(nk)). The weight and distance update is constant for each voxel. The final surface extraction is at most (n).
- **[JD]**
- **[LF]**
- **[MK]**
  Theoretically, the space/time is O(n^1.5) since the authors define a function over a voxel grid. However, using run-length encoding, the algorithm is reduced to linear. Furthermore, the implementation is easy to parallelize.

6. How could the approach be generalized?

- **[AS]**
  This approach can be generalized to include estimated surface normals. This will improve reconstruction around corners and thin surfaces.

- **[DS]**
  A possible extension is improving the execution time of the space carving algorithm and demonstrating parallelization of the whole algorithm.
- **[FP]**
  As the authors claim, their approach may be adapted to other types of acquisition technologies. Particularly, the distance and weighting function are two parameters that may be adjusted according to the scanning device.
  Other interesting specialization of their method may involve large scale objects or scene reconstruction. This situation also leads to formulate interesting problem such as optimization of a capture plan. (How should the object be captured to minimize the number of range image required in reconstruction?).
  The parallelization of their algorithm is also suggested by the authors as a valuable extension.
- **[JD]**
- **[LF]**
- **[MK]**
  One approach may be to try to adapt the radius of blending to the point distribution.

7. If you could ask the authors a question (e.g. “can you clarify” or “have you considered”) about the work, what would it be?

- **[AS]**
  Can you clarify how the range data is weighted?
- **[DS]**
  How do you obtain the weight function and how do you incorporate the error from the scanning technology? What methods do you use to register multiple scan images?
- **[FP]**
  In the context of optical range scanners, it is possible to *a priori* define a capture plan for a given object? (i.e., how many captures you require and from which point of views), or does the scanning rely in a progressive region filling process?
- **[JD]**
- **[LF]**
- **[MK]**