Building Accurate Geometric Models from Abundant Range Imaging Information

CARL DIEGERT, JOHN SACKOS, AND ROBERT NELLUMS

SANDIA NATIONAL LABORATORIES, BOX 5800, ALBUQUERQUE NM, 87185-1109

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Abstract

We define two simple metrics for accuracy of models built from range imaging information. We apply the metric to a model built from a recent range image taken at the Laser Radar Development and Evaluation Facility (LDERF), Eglin AFB, using a Scannerless Range Imager (SRI) from Sandia National Laboratories. We also present graphical displays of the residual information produced as a byproduct of this measurement, and discuss mechanisms that these data suggest for further improvement in the performance of this already impressive SRI.

Introduction

Extracting geometric models from the abundant, inexpensive range imaging information produced by Sandia's Scannerless Range Imaging (SRI) technology [1], [2] is pivotal to making these data useful in targeting, navigation, and many other applications. Together with the tremendous value added by summarizing megabytes of raw, range image information in thousands, or even hundreds of bytes of geometric model information comes an opportunity to inadvertently degrade the value of these data by overreduction. This paper measures the accuracy of a system that both senses and automatically builds models to summarize the simplest of features in a scene. We also present graphical displays of the residual information produced as a byproduct of measuring accuracy, and discuss opportunities that these data suggest for further improvement in the performance of this already impressive SRI.

! CFD: Email: diegert@cs.sandia.gov; telephone 505-845-7193. For full-color versions of many of the figures in this paper, please visit <http://www.cs.sandia.gov/~diegert>.

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Experimental Detail

Measuring accuracy of models built from range imaging information is complex. In this paper we define and carefully measure two simple, fundamental parameters. To evaluate these metrics, one must obtain a range image of a scene that includes a few planar surface patches, and must apply model-building algorithms to find plane equations to estimate the locations of these surfaces. The first metric summarizes how closely the models fit the range measurements. The second metric summarizes how closely the model corresponds to the true position of the surfaces in the scene.

Figure 1. Upper left of figure is a *resolution target* at the Eglin AFB LDERF. The overall dimension of the front, rectangular face is 4.80 meters by 8.80 meters. Upper right of figure is measurement of the distance to the movable back planar surface that is exposed through the cutouts in the front surface. Bottom of figure is of the Sandia National Laboratories Scannerless Range Imager at dusk, measuring to this target from a distance of approximately 500 meters. The acquisition analyzed here was actually taken in daylight, when the green beam is far less visible. Other acquisitions in this series included targets at up to a kilometer range. (Full color versions of many of the figures in this paper are at <http://www.cs.sandia.gov/~diegert>.)

The planar surface in the range image should be large enough to include at least a few hundred range measurements (range pixels), to provide reliable assessment of the error distribution. The observed planar surface need not fill the field of view. Orientation of the planar surfaces should be approximately perpendicular to the range imager's line-of-sight. At the edge of an observed planar region, an instrument's dynamic ability to measure steps in ranges may contribute to range errors. We suggest that range measurements near such transitions be excluded, so that any such contribution is isolated from the simple accuracy of building models of the interior of planar surfaces.

FIRST METRIC

The first step in computing the accuracy metric is to define the region-of-interest (ROI) corresponding to the interior of a known planar feature in the range image. This ROI may be comprised of a few disconnected subregions. For example, observations of the north and south ends of a planar building wall may be usable, while the middle of the wall is obscured by a tree. The second step is to estimate a plane equation from the ranges in the ROI. The third step is to form the *signed residuals* by computing the distance between each range measurement in the ROI and the fitted plane equation.

In general, it may be difficult to summarize the information in the signed residuals to form our first accuracy metric. Here we

presume that a *least-squares* estimate constructs the plane chosen in step two, and that the resulting signed residuals (step three) have, approximately, a Gaussian distribution. In this case, the root-mean-square (RMS) of the signed residuals is a useful accuracy metric.

SECOND METRIC

The second accuracy metric is formed from the positions of models for two parallel, planar patches in the imaged scene. The distance between the two fitted planar patches is compared to a *ground truth* measurement of the distance between the two surfaces.

Figure 2. The SRI system positioned in the LDERF indoor laser laboratory, approximately 500 meters from the target, for an acquisition on February 19, 1997. The SRI receiver, as configured for this acquisition, comprises components 1-3, and the transmitter is component 4:

1. Kodak model 1.6i CCD camera, 1532 horizontal by 1024 vertical square pixels (s/n 61739N6C542).
2. Nikor Reflex 500mm, f6 lens (s/n 210131) with 532nm narrow band filter.
3. Modified, Gen3 image intensifier and custom electronics assembly to control the modulation applied to both the image intensifier and the laser transmitter. (Unit 3.)
4. Frequency-doubled, Nd:Yag diode-pumped laser from Big Sky, with a single, negative lens to diverge the collimated beam.

A computer and its software (neither is visible in the figure) complete the SRI system.

Figure 3. The right image in this pair of images is formed from a 366 pixel high by 774 pixel wide raster of range pixels cropped from the 1534 by 1024 range image, and is presented without any geometric correction. Within a single range ambiguity, lighter values are closer to the SRI. The range ambiguity is 18 meters.

The left image is a region from the right image, overprinted with color to code the region of interest for the close plane (three disjoint, approximately rectangular regions shown in blue herringbone), and the far plane (two disjoint, approximately rectangular regions shown in red diamonds). These ROI definitions exclude pixels near steps in range.

APPLICATION TO ACQUISITION AT EGLIN AFB SITE C-3

Next, we describe a range-image acquisition and our evaluation of the two performance metrics. On February 19, 1997, we imaged a unique range-imaging resolution target at Eglin AFB site C-3, shown in Figure 1. This superb target is part of the Laser Radar Development and Evaluation Research Facility (LDERF²). The target offers a wealth of calibration possibilities beyond the simple two presented here. Figure 2 identifies the SRI components as they were configured for this acquisition. The patented SRI technology is described elsewhere [1], [2].

Figure 3 shows the two ROIs we defined to measure the near and far planar surfaces of the target. We then applied a software system we are developing for automatic model building to fit two plane equations, one each to the projected range pixels in each ROI. In addition to reporting the coefficients of the fitted equations and statistics on their fit, this software constructs and saves geometry descriptions of planar polygons that correspond to the fitted points. We also used the software system to form meshes with quadrilateral facets, whose vertices are the unfiltered range pixels in each ROI. Figure 4 shows the screen as it appears when using the Microsoft Softimage Creative Environment to after loading these saved geometries, and arranging for an orthographic view from above the fitted planar facets.

² An overview of the LDERF facility appears at <http://www.wlmmn.eglin.af.mil/public/facility/ldarf.html>.

Table 1. Sample size, n , centroid, (x,y,z) , and fitted plane equation, $ax + by + cz + d = 0$, for range pixels in two regions of interest. The coordinates are Cartesian, with the first coordinate direction to the right, relative to the look direction, the second up, and the third toward the instrument. The rightmost two columns give the estimated standard error, s , and the maximum of the absolute error, m , for each ROI.

All measurements in this table are in centimeters.

	n	x	y	z	a	b	c	d	s	m
Close Plane	17,233	-78.54	243.55	-122.29	-10.8487	-1.4697	99.398	116.61	3.51	13.27
Distant Plane	11,290	-69.07	244.11	-135.26	-11.5885	-1.8735	99.309	130.89	3.45	14.95

Results

The first metric for accuracy in building models from range imaging information is the estimated standard error of differences in the ranges about the fitted model. We obtained a standard error of about 3.5 centimeters (1.4 inches), as shown in Table 1. The worst error, over all 29,523 range measurements, was under 15 cm (5.9 inches).

Figure 4. Orthographic view of fitted, trimmed plane models (in white), and of the unfiltered range pixels connected in a mesh (in black). The exact viewpoint for this view is rotated slightly in both pitch and yaw, to look directly down on the fitted planes, and to make the planes perpendicular to the scale. The scale is in meters.

The second metric for accuracy records how the models we built fit the true positions of the planes. To compute the second metric, we assumed that the front and back panels of the target are perfectly flat, parallel, and separated by 13.6525 centimeters (5.375 inches). The two fitted planes are not parallel (the angle between their gradient vectors is 0.487 degrees), since we computed independent least-squared fits. A perfectly correct evaluation of the second metric should compute a simultaneous fit under an assumed model that constrains the fitted planes to be parallel. Instead, we evaluated the distance from the centroid of the distant plane (a point on the distant plane), to the near plane. We found that our fitted models are separated by 13.93 cm. (5.49 in.), an error of about 0.28 cm. (0.11 in.).

Our point estimate for the second metric indicates that we overestimate the true distance by 0.28 cm. We should place this estimate in

Figure 5. Front and back views of the same geometries. In blue are the five fitted polygons, three trimmed from the fitted near plane, and the other two trimmed from the far fitted plane. In gray is a mesh formed by connecting the unfiltered range pixels. In the front view (top), range pixels closer than the fitted plane are visible, while the fitted polygon obscures those farther away. The back view (bottom) shows the range pixels obscured in the front view. The fitted polygons are approximately rectangular, with height 320 cm., and width 80 cm. The standard error of the residuals is about 3.5 cm.

Considerable correlation structure is apparent in these views, and may suggest improvements in the SRI.

the context of our *ground truth* on the actual target. We were only able to measure separation at the bottom of the two rectangular cutouts, as shown in Figure 1. The 5 and 3/8 inches we measured there may not apply over the whole of our ROIs. The construction drawings for the target specify a tolerance of 0.5 cm.

ANALYSIS OF RESIDUALS

Careful study of residual errors about a fitted equation can be of enormous value [3]. The residual plots in Figure 5 show patterns of correlation between spatially close errors.

Conclusions

An old adage is that if you can't measure something, you can't improve it. We are confident that the two metrics we have described will allow us to evolve the SRI technology. We anticipate building instruments to measure with accuracy better than the 3.5 cm. (1.4 in.) reported here, and in building less expensive instruments that retain 3.5 cm. accuracy.

The spatial correlation of the range errors suggests some further work that may improve the accuracy of models obtained from the SRI technology. We would like to revisit the Eglin target and obtain better measurements of its actual geometry using a slow but accurate Leica survey instrument. If the target proves flat to better than the 0.5 cm. accuracy specification, then we will look for sources of error in the SRI. We plan to take SRI measurements to determine if errors are consistent from one image to the next. If we discover consistent errors, we should be able to construct calibration tables to remove these errors as part of the model building computation. We envision a process where a table of correction coefficients are automatically optimized for each SRI during manufacture, and are burned into each

instrument. This process is similar to that used to correct for pincushion distortion in CRT displays. If the ripples in the errors apparent in Figure 5 turn out to be due to, say, variations in thickness of the phosphor in the image intensifier, and if these variations are stable over time and temperature, then we can correct for these errors using proper calibration, just as the pincushion adjustments correct for variations in a CRT's deflection coils.

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