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Using Quality Metrics with Laser Range Scanners *

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Adaptive Laser Range Scanning using Quality Metrics

David MacKinnon, Victor Aitken, and François Blais

Abstract—We present an approach to laser range scanning in which quality metrics are used to automatically reduce the number of measurements acquired from a scanner viewpoint in order to guide a minimally trained operator through the scanning process. As part of this approach we present improved versions of the orientation and reflectivity quality metrics, and introduce six new within-scan quality metrics: outlier, enclosed, resolvability, planarity, integration, and aliasing. These metrics are combined to generate a total within-scan quality metric for each measurement in the scan. The orientation, resolvability, reflectivity and planarity quality metrics are used to divide the total field of view into regions based on their likelihood to produce useful measurements. A series of small high-density raster scans is then automatically generated to cover regions automatically identified as having a significant likelihood to produce useful measurements. All scans are then merged to generate a composite range image. The total number of measurements in the composite range image is minimized by merging statistically close measurements using a minimum variance estimator weighted by the total within-scan quality of each measurement.

Index Terms—adaptive scanning, quality metrics, range imaging, automated scanning, operator-guided scanning

I. INTRODUCTION

Currently absent in the field of medium- to large-volume scanning is an interactive system capable of automatically obtaining a complete high-quality model of a scene or object *in situ* using an automated system, or by guiding a minimally-trained operator through the scanning process [1], while minimizing the number of measurements acquired. Some attempts have been made, most notably the work of Sequeira *et al.* [2], Blais *et al.* [3], and Callieri *et al.* [4]. Sequeira *et al.* used *quality metrics* for merging range images and, to a limited extent, for next-best-view (NBV) planning. Blais *et al.* iteratively merged multiple low-density scans until a stable model was achieved. Callieri *et al.* used a multi-stage approach, first developed by Scott *et al.* [5] for small-volume scanning, in which an initial low-density scan is followed by a series of high-density targeted scans. In this paper, a multi-stage approach is presented in which quality metrics are used to adapt the scanning process such that the total quality of the final range image is maximized while minimizing the number of measurements acquired. Unlike Callieri *et al.*, this approach uses the strengths of each quality metric to tailor the scanning process to the surface being scanned.

The quality of a range measurement depends on measurement uncertainty and measurement resolution; however,

spatial uncertainty is also strongly affected by other environmental factors such as the type of surface material [6], surface reflectivity [7], distance to the surface [7] [8], and incidence angle [9]. These environmental conditions must be detected in the data and combined with model-based uncertainty as metrics that further describe the quality of the virtual model. Few quality metrics exist in contemporary literature, and those that do are limited in scope. They are often not used in conjunction with the physical properties and limitations of the scanner and/or surface. In this paper a low-density raster scan is used to perform a cursory examination of the environment, then various environmental factors are quantified using general-purpose quality metrics that relate to the physical properties of the scanner. These metrics are then used to both determine the quality of the measurements collected, and to direct the scanning process such that the potential quality of the resulting composite range image is maximized with respect to the scanner limits while minimizing total scan time.

II. PROPOSED APPROACH

In this section, we introduce a series of both new and improved quality metrics. In all cases, the quality metric has a value in the range $C_i^{metric} = 1$ (ideal quality) to $C_i^{metric} = 0$ (unacceptable quality) where *metric* refers to any metric presented in this paper. We then describe how these quality metrics can be used to perform adaptive scanning. Finally, we show how these metrics are combined into a within-scan total quality metric, as well as how they can be used to perform a quality-weighted merge of subscans.

A. New Quality Metrics

The *outlier quality metric* C_i^{out} represents the reduction in confidence in a measurement after its spatial position has been changed during typical pre-processing activities such as smoothing. It is found by

$$C_i^{out} = \begin{cases} 1 & \Delta R_i^{shift} \leq R_i^{err} \\ \frac{R_i^{err}}{\Delta R_i^{shift}} & \text{otherwise} \end{cases} \quad (1)$$

where R_i^{err} is a range error margin based on the range measurement uncertainty. The change in range value $\Delta R_i^{shift} = |R_i^{initial} - R_i^{final}|$ where the range measurement prior to post-processing is represented by $R_i^{initial}$ and the range measurement after post-processing is represented by R_i^{final} .

The *resolvability quality metric* C_i^{res} is used to identify regions that cannot be resolved at the desired surface resolution Δx given the current scanner viewpoint to within a

margin of error. This metric is found by

$$C_i^{res} = \begin{cases} 1 & d_i^{len} \leq d_i^{up} \\ \frac{d_i^{up} - d_i^{width}}{d_i^{len} - d_i^{width}} & d_i^{width} < d_i^{up} < d_i^{len} \\ 0 & d_i^{up} \leq d_i^{width} \end{cases} \quad (2)$$

where d_i^{len} is the length of the long axis of the beam footprint, d_i^{width} is the length of the short axis, and $d_i^{up} = \Delta x + 2d_i^{err}$ is the desired surface resolution with an error margin based on the measurement rotational uncertainty.

The *planarity quality metric* C_i^{planar} indicates whether the surface within the 8-neighbourhood of $\mathbf{p}_i$ is locally planar. A measurement $\mathbf{p}_i$ that is contained within a locally planar neighbourhood [10] is assigned $C_i^{planar} = 1$; otherwise, it is assigned $C_i^{planar} = 0$.

The *aliasing quality metric* C_i^{alias} is related to the resolvability quality metric, but represents the likelihood that a scan is sufficiently dense to ensure that features at the desired surface resolution will be detected. The aliasing quality metric is found by

$$C_i^{alias} = \begin{cases} 0 & d_i^{up} \leq d_i^{far} \\ 1 - \frac{d_i^{far} - d_i^{low}}{2d_i^{err}} & d_i^{low} < d_i^{far} < d_i^{up} \\ 1 & d_i^{far} \leq d_i^{low} \end{cases} \quad (3)$$

where d_i^{far} is the distance to farthest 8-neighbour of $\mathbf{p}_i$, and $d_i^{low} = \Delta x - 2d_i^{err}$. Measurements previously marked as planar ($C_i^{planar} = 1$) always have $C_i^{alias} = 1$ because planar surfaces lack spatial surface features. The aliasing metric is assigned $C_i^{alias} = 0$ if any of the 8-neighbours of $\mathbf{p}_i$ are non-return or are outside the Volume of Interest (Vol).

The *integration quality metric* represents the level of confidence in the accuracy of range measurements obtained using triangulation and continuous-wave laser range scanners which can be affected by the distance the laser travels during the acquisition period. Speckle noise arises when speckle elements on the surface illuminated by the laser spot are large when compared to the wavelength of the laser light [11] [12], and is generally countered by integrating a single measurement over several intensity samples as the laser spot is moved over the surface being scanned [13]. This is complicated by the need to minimize aliasing by ensuring that the measurements are separated by a distance less than the radius of the laser spot [14]. The integration quality metric is obtained using

$$C_i^{int} = \begin{cases} 1 & \theta_i^{int} \leq \theta_i^{rad} \\ \frac{\theta_i^{rad}}{\theta_i^{int}} & \text{otherwise} \end{cases} \quad (4)$$

where θ_i^{int} is the rotational distance between measurement $\mathbf{p}_i$ and the measurement $\mathbf{p}_{i-1}$ that immediately preceded it, and θ_i^{rad} is the radius of the laser spot in units of rotational distance. The integration metric is assigned $C_i^{int} = 0$ if $\mathbf{p}_{i-1}$ is not in the same scan line, or if either $\mathbf{p}_i$ or $\mathbf{p}_{i-1}$ is a non-return measurement.

B. Improved Quality Metrics

The *orientation quality metric* C_i^{orient} is found using

$$C_i^{orient} = \begin{cases} 0 & c\gamma_i \leq c\gamma_{max} \\ \frac{c\gamma_i - c\gamma_{max}}{1 - c\gamma_{max}} & \text{otherwise} \end{cases} \quad (5)$$

where $c\gamma_i = \cos(\gamma_i)$ and $c\gamma_{max} = \cos(\gamma_{max})$ in which γ_{max} is the user-defined maximum acceptable surface orientation with respect to the laser path. Surface orientation is a commonly-used quality metric [15] [16] [17]; however, previous versions of this metric did not employ a maximum acceptable surface orientation as part of the metric.

The *reflectivity quality metric* C_i^{refl} is defined by

$$C_i^{refl} = \begin{cases} 0 & \rho_i \geq \rho_{max} \\ \frac{\rho_{max} - \rho_i}{\rho_{max} - 1} & \rho_{max} > \rho_i > 1 \\ 1 & \rho_i = 1 \\ \frac{\rho_i - \rho_{min}}{1 - \rho_{min}} & \rho_{min} < \rho_i < 1 \\ 0 & \rho_i \leq \rho_{min} \end{cases} \quad (6)$$

where ρ_{min} and ρ_{max} are user-defined bounds on the acceptable reflectivity of the surface, and ρ_i is the surface reflectivity relative to a reference surface. Fiocco *et. al.* [17] had previously defined a reflectivity quality metric as a binary quality metric; however, their approach reduces the generalizability of the metric.

C. Region-based Adaptive Scanning

Region-based adaptive scanning consists of extracting the regions of the TFoV that correspond to the surface of interest, then scanning only those regions likely to contribute useful and non-redundant information to the model of the object being scanned. A low-density 256×256 anchor scan is performed to initialize the region map; however, prior to acquiring the anchor scan, the system guides the operator through the anchor scan acquisition process by iteratively suggesting an alternative scanner viewpoint that should yield a better quality anchor scan. The process terminates when no alternative scanner viewpoint would yield a sufficiently better quality anchor scan.

Scan quality is based on the *weighted spot size* W_i^{spot} of each measurement, defined by

$$W_i^{spot} = w(\zeta_i)(1 - C_i^{orient}C_i^{res}) \quad (7)$$

where $w(\zeta_i)$ is the radius of the laser spot assuming the surface normal is oriented along the laser path, and ζ_i is the distance to the beam waist. The volume bounded by $w(\zeta_i)$ represents the region within which 86.5% of the beam irradiance is contained [18] [19].

Once the anchor scan has been obtained from a viewpoint that maximizes the anchor scan quality, a region map is generated to identify the portions of the TFoV that require rescanning to improve the quality of the composite range image, which portions are likely to yield redundant measurements, and which portions are likely to yield unacceptable measurements. These regions are referred to as the *Rescan*

region, the *Complete region*, and the *Unscannable region* respectively.

The Unscannable region is defined by all measurements in which the *exclusive quality product* $C_i^{excl} = 0$, all non-return measurements, and all measurements outside the VoI. The exclusive quality product is found by

$$C_i^{excl} = C_i^{refl} C_i^{res} C_i^{orient}. \quad (8)$$

The Complete region is initially defined by all measurements in which the *planarity quality metric* is $C_i^{planar} = 1$. Sobel edge detection [20] is then used to transfer measurements surrounded by rapidly changing reflectivity quality values from the Complete region to the Rescan region. Finally, measurements in which the outlier quality value is less than an experimentally determined threshold $C_{threshold}^{out}$ are moved from the Complete region to the Rescan region, indicating that the spatial measurement changed significantly during pre-processing.

A series of dense 256×256 subscans is automatically generated for one of two operational modes. In the *fast-scan mode* (FS-mode), the inter-sample separation is chosen to maximize the likelihood of achieving a predefined resolution Δx while minimizing the number of subscans obtained. The FS-mode inter-sample separation is defined by

$$\theta^{sep} = \min_{i=1}^N \{\theta_i^{\Delta x} - \theta_i^{err}\} \quad (9)$$

where $\theta_i^{\Delta x}$ is the rotational distance defined by the desired surface resolution Δx and the surface orientation γ_i with respect to the laser path, and θ_i^{err} is an error margin based on the rotational measurement uncertainty of the scanner. In the *detail-scan mode* (DS-mode), the inter-sample separation is chosen to ensure that surface features can be resolved to smallest size of the laser spot on the surface. The DS-mode inter-sample separation is defined by

$$\theta^{sep} = \min_{i=1}^N \{\theta_i^{res} - \theta_i^{err}\} \quad (10)$$

where θ_i^{res} is the rotational distance defined by the rotational resolution of the scanner. In either case, the subscans are positioned to maximize coverage of the Rescan region while minimizing coverage of the Unscannable region.

A *total within-scan quality metric* C_i^{total} is generated for each measurement prior to merging all subscans with the anchor scan to generate a composite range image (CRI). The total within-scan quality metric C_i^{total} is obtained using

$$C_i^{total} = C_i^{excl} \frac{1 + C_i^{aug}}{2} \quad (11)$$

where C_i^{aug} is the *augmenting quality average*. The augmenting quality average C_i^{aug} is found by

$$C_i^{aug} = \frac{C_i^{planar} + C_i^{enc} + C_i^{int} + C_i^{alias} + C_i^{out}}{5} \quad (12)$$

where C_i^{enc} is the *enclosed quality metric*. If a measurement is completely enclosed within an 8-neighbourhood then $C_i^{enc} = 1$ (enclosed); otherwise, $C_i^{enc} = 0$ (non-enclosed).

D. Quality-based Merging

A CRI is initialized with all measurements from the anchor scan. All measurements from each subscan are then extracted and the rotational distance between each subscan measurement and the rotationally closest (corresponding) measurement in the CRI is determined. Subscan measurements in which the rotational distance is less than the χ^2 difference between measurements are then selected to be merged using the *quality-weighted modified Kalman minimum variance* (weighted-MKMV) estimation method.

The weighted-MKMV method involves weighting the covariance matrices with the total within-scan quality associated with the measurement. Given a measurement $\mathbf{p}_{CRI,i}$ in the CRI with total within-scan quality $C_{CRI,i}^{total}$ and its corresponding subscan measurement $\mathbf{p}_{sub,i}$ with total within-scan quality $C_{sub,i}^{total}$, the measurement $\mathbf{p}_{CRI,i}$ is updated using

$$\mathbf{p}_{CRI,i} = W_{CRI,i} \mathbf{p}_{CRI,i} + W_{sub,i} \mathbf{p}_{sub,i} \quad (13)$$

where

$$W_{CRI,i} = W_i^{-1} C_{CRI,i}^{total} \Sigma_{CRI,i}^{-1} \quad (14)$$

and

$$W_{sub,i} = W_i^{-1} C_{sub,i}^{total} \Sigma_{sub,i}^{-1} \quad (15)$$

are the weighting parameters. In these equations, $\Sigma_{sub,i}$ is the covariance of $\mathbf{p}_{sub,i}$ and $\Sigma_{CRI,i}$ is the covariance of measurement $\mathbf{p}_{CRI,i}$. The W_i term is found using

$$W_i = C_{CRI,i}^{total} \Sigma_{CRI,i}^{-1} + C_{sub,i}^{total} \Sigma_{sub,i}^{-1} \quad (16)$$

where $C_{CRI,i}^{total}$ and $C_{sub,i}^{total}$ are scalar. The covariance matrix for $\mathbf{p}_{CRI,i}$ is then updated using

$$\Sigma_{CRI,i} = \frac{1}{C_{CRI,i}^{total} + C_{sub,i}^{total}} W_i^{-1}. \quad (17)$$

The process of updating the composite range image with each subscan proceeds as follows:

- If $C_{CRI,i}^{total} > 0$ and $C_{sub,i}^{total} > 0$ then the weighted-MKMV method is used.
- If $C_{CRI,i}^{total} = 0$ and $C_{sub,i}^{total} = 0$ then $\mathbf{p}_{CRI,i}$ and $\Sigma_{CRI,i}$ are updated using the MKMV estimator method [21] [22].
- If $C_{CRI,i}^{total} > 0$ and $C_{sub,i}^{total} = 0$ then $\mathbf{p}_{CRI,i}$ and its associated covariance matrix $\Sigma_{CRI,i}$ are unchanged.
- If $C_{CRI,i}^{total} = 0$ and $C_{sub,i}^{total} > 0$ then $\mathbf{p}_{CRI,i}$ is assigned the value of $\mathbf{p}_{sub,i}$ and $\Sigma_{CRI,i}$ is replaced with $\Sigma_{sub,i}$, the covariance matrix associated with $\mathbf{p}_{sub,i}$.

Finally, the total within-scan quality is updated such that

$$C_{CRI,i}^{total} = \max\{C_{CRI,i}^{total}, C_{sub,i}^{total}\}. \quad (18)$$

III. RESULTS

Table I shows the sequence of initial and predicted average weighted spot sizes W^{spot} for the test surface that consisted of a plastic planter, a poster board and a picture of distributor caps. In this experiment, the scanner was repositioned as directed by the system until the requested translational adjustment was at or less than 1 centimetre, the requested

TABLE I
SCANNER PLACEMENT FOR ANCHOR SCAN USING PREDICTED
WEIGHTED SPOT SIZE REDUCTION

Initial W^{spot}	Predicted W^{spot}	Requested Translation (m)	Requested Rotation
7.323	0.564	X=0 / Y=0 / Z=1.0	$\theta=5^\circ$ / $\phi=12^\circ$
0.414	0.414	X=0 / Y=0 / Z=0.0	$\theta=-2^\circ$ / $\phi=2^\circ$

TABLE II
REDUCTION IN TOTAL SCAN TIME USING ADAPTIVE SCANNING

Object	Number of subscans	Total Scan time	TFoV Scan time	Fraction of TFoV scan time
FS-mode	35	6.16 min	109.89 min	0.056
DS-mode	241	42.44 min	109.89 min	0.386

rotational adjustment was at or less than 5 degrees, or there was no predicted improvement in W^{spot} . Figure 1 shows the FS-mode rescan map for the test surface. Solid boxes represent the effective scanning region while the dashed boxes represent the area covered by the raster scan.

Fig. 1. Final Region Map with subscans. The Unscannable region is in white, the Rescan region is in dark grey, and the Complete region is in light grey. Each box represents a single subscan.

Table II shows the reduction in scan time compared to a full, or non-adapted, scan of the TFoV. The effect of adapting the scanning strategy based on analysis of the anchor scan resulted in a reduction in total scan time to 5.6% when using the FS-mode to just achieve a surface resolution of $\Delta x = 0.002$ metres. When using DS-mode scanning, the adaptive scanning approach required 38.6% the time that would be required for a TFoV scan at maximum resolution. The scan times in Table II do not include time for data processing, data transfer, or moving the scanner.

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