ADVANCEMENTS IN LiDAR-BASED REGISTRATION OF FIA FIELD PLOTS

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Abstract.—Meaningful integration of National Forest Inventory field plot information with spectral imagery acquired from satellite or airborne platforms requires precise plot registration. Global positioning system-based plot registration procedures, such as the one employed by the Forest Inventory and Analysis (FIA) Program, yield plot coordinates that, although adequate for some purposes, often contain substantial error. Conversely, the registration of Light Detection and Ranging (LiDAR) data is accurate and precise. Considering the proliferation of high density LiDAR data, there is potential to substantially improve plot registration. Earlier attempts were not successful because they relied solely on the relative location of mapped tree stems and local maxima in vegetation surfaces generated from the LiDAR data. In this study, registration is achieved by examining the correlation between plot canopy surfaces generated by using the FIA field data and modeled tree crowns and the corresponding vegetation surface derived from the LiDAR data. With the LiDAR vegetation surface remaining stationary, the modeled surface is jittered in two dimensions at regular intervals, and the correlation is computed for each moving instance. Assuming that it satisfies a set of consistency criteria, the moving instance for which correlation is maximized yields the plot coordinates. Gains in computational efficiency are realized via parallelization. Results from eastern Oregon show that precise—better than 2 m—registration is achieved for 80 percent of the investigated FIA plots.

INTRODUCTION

Meaningful integration of remotely sensed and forest inventory field plot data requires precise plot registration. Where this requirement is not met, the energy returned to the remote sensing instrument corresponds poorly to the trees on the plot. Spatial discrepancies between remotely sensed data and plot locations compromise the strength and validity of modeling and diminish the utility of the data. It has been shown that the effects of registration issues become more pronounced with smaller field plot sizes (Fluwelling 2009, Frazer et al. 2011), and shorter spatial continuity in the inventory parameter of interest (Gobakken and Næsset 2009, Goodchild et al. 1993).

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Most National Forest Inventory (NFI) programs, such as the Forest Inventory and Analysis (FIA) Program of the U.S. Forest Service, have collected field plot location primarily to facilitate future navigation to permanent plots. Historically, plot coordinates were obtained via several methods, including manual transfer from orthophotos and digital raster graphics, and, since the mid-1990s by using global positioning system (GPS) technology. Repeated visits to permanent plots generated multiple coordinates for each plot. Rather than accepting the latest as the most accurate, the Pacific Northwest FIA Program (PNW-FIA) designed and implemented a procedure, known as plot grid management (PGM), which evaluates all coordinates for each plot and selects the one “most accurate.” Anecdotal evidence suggests that PGM and continuous advancements in GPS technology have improved coordinate accuracy but precision issues remain. PNW-FIA’s past efforts to improve plot coordinates by using high resolution airborne imagery from the National Agricultural Imagery Program (NAIP) and manual interpretation were limited by the NAIP imagery's poor registration, obliqueness, and inadequate contrast.

Unlike NAIP and most satellite imagery, data acquired with Light Detection and Ranging (LiDAR) technology have negligible registration errors, are unaffected by sun angle and shadows, and when collected at high density provide detailed, three-dimensional (3D) characterizations of tree crowns and terrain. Gatziolis (2009) used a variant of the world-view algorithm to register fixed-radius, FIA-like plots in the temperate rainforest of Oregon. He linked 3D point patterns obtained by processing the LiDAR return cloud and corresponding to the locations of identified individual tree tops to point patterns generated from field plot data. Of 45 plots in the study area only 3 (11 percent) were registered with submeter precision, although for 18 more (40 percent) registration precision ranged between 1 and 5 m. A similar approach (Dorigo et al. 2010) was evaluated in Austria using lower density LiDAR data and variable radius inventory plots. It, too, relied on matching tree tops derived from plot data to tops identified on a LiDAR-derived vegetation height surface. The plot location was determined iteratively as the one that minimized the weighted sum of height differences between matched trees. It was reported that 67 percent of plot centers were registered within 4 m from of location identified by an image analyst.

While these approaches improved the registration for most plots, registration was precise (<2 m) for very few. By matching only tree tops, potentially valuable information on the shape and spatial arrangement of individual crowns and canopy openings is not utilized. Investigations that incorporate crown shape and spatial distribution into plot registration techniques are therefore warranted, especially when considering the recent proliferation of publicly available, high density LiDAR data acquisitions that can support these techniques. One such effort is explored and evaluated in this study. To enhance potential application, technique development focused on full automation, computational efficiency, quantitative criteria that determine plot registration success or failure, accommodation of standard and clustered plot designs, and dynamic adjustment to local vegetation structure conditions.

STUDY AREA AND METHODS

The Malheur National Forest in eastern Oregon is dominated by open, mostly coniferous forests and gentle terrain. Discrete return, high density LiDAR data of approximately nine returns per square meter were acquired over the entire Forest in 2007 and 2008. A 0.91-m ground digital elevation model (DEM) was provided by the data vendor. A highest-return Canopy Height Model (CHM) was derived by subtracting DEM values from the elevation value of each return, as a 0.5-meter raster. Individual tree crowns were delineated via the valley-following algorithm on a smoothed version of the CHM and the location of each tree top was recorded (Fig. 1).

For each subplot of the 82 FIA plots within the study area field-visited within 2 years of the LiDAR acquisition date, 3D models were developed using field assessed tree location relative to subplot center, height, and species. Each subplot model was constructed using species-specific crown shapes ranging from conical to ellipsoidal or weighted combinations of the two, and modeled estimates of crown radius and length (Donnelly 1997, Shaw 2009). The ensuing 3D subplot representation was then rasterized to form a 0.5-m Subplot Height Model (SHM); crown portions outside the subplot boundary were excluded (Fig. 2). The retrieval of subplot center coordinates was based on the correlation between the stationary CHM and instances of the corresponding SHM moving at one-cell increments within a 40 by 40 m window centered at the initial coordinates retrieved from the production FIA database.

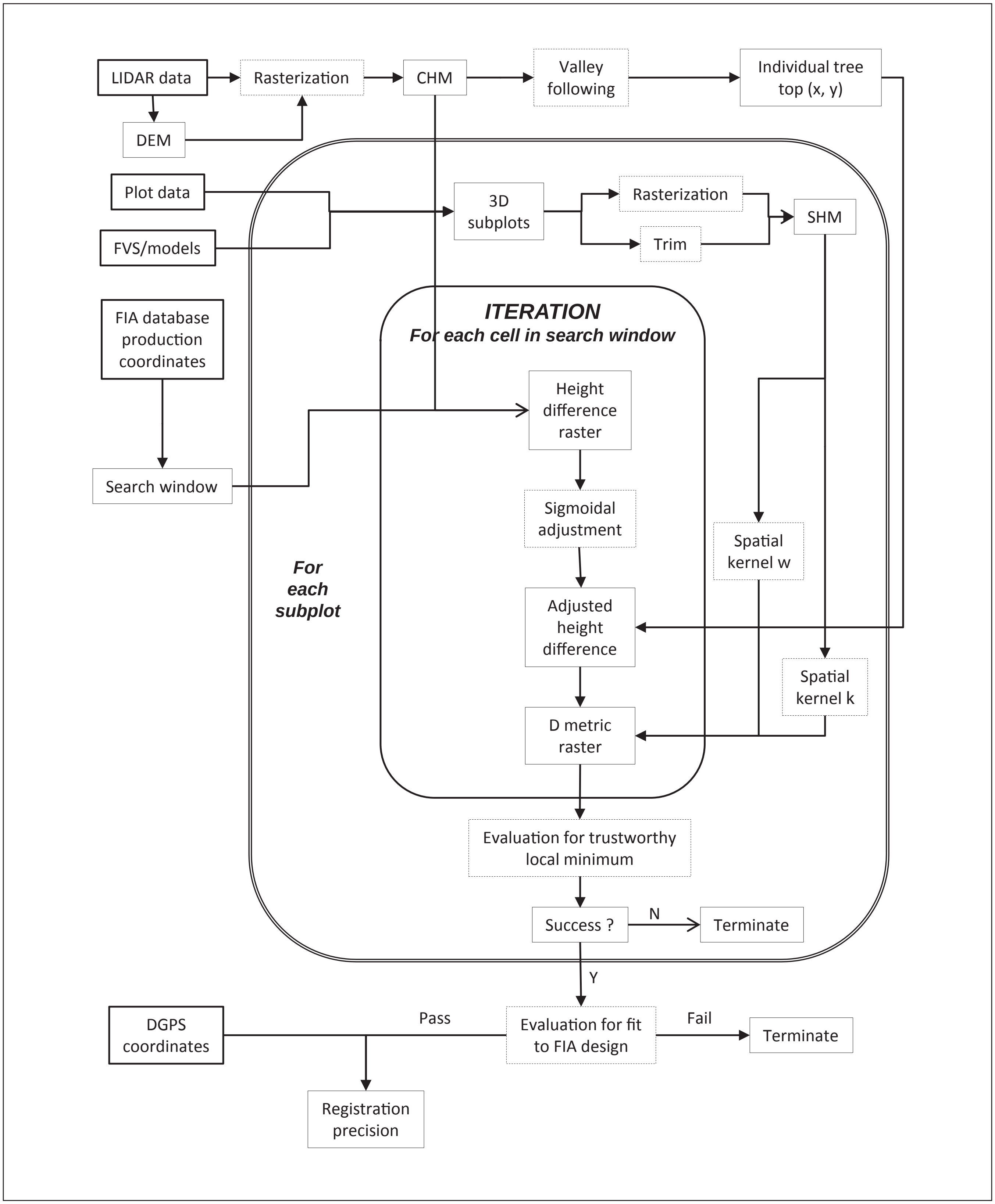

Figure 1.—Flow chart of the registration process. See text for acronym definitions.

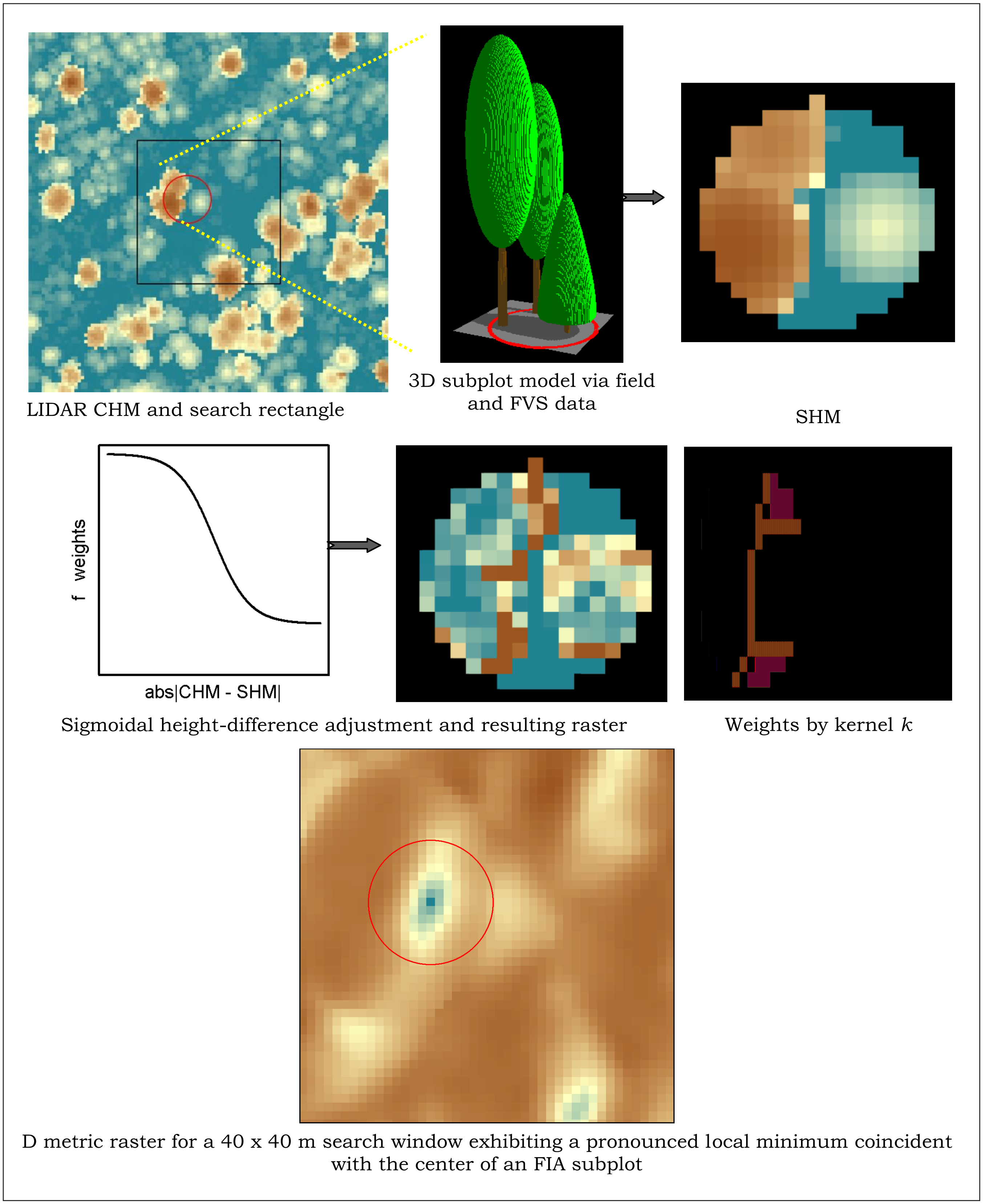

Figure 2.—Illustration of the LiDAR data-based registration for an FIA plot. Darker raster tones indicate higher values or weights. See text for acronym definitions.

The correlation metric D

$$D = \sum_{i}^{N} f_i w_i k_i \left| CHM_i - SHM_i \right| \qquad [1]$$

across the search area was computed as the sum of absolute height differences between CHM and each SHM instance scaled by a nonspatial function *f* and two spatial kernels *k* and *w*. Note that N in Equation (1) denotes the number of cells in a subplot. Function *f* has sigmoidal form. The slope of the sigmoid is inversely related to crown height variability (steeper for uniform canopies). Kernel *k* is computed once for each SHM as the distance between cells with openings (defined as those with SHM <2 m), and vegetation cells (Fig. 1). Kernel *w* assigns low weight to all cells in SHM instances corresponding to crowns in the CHM with their top outside the boundary of the subplot instance. Kernel *w* neutralizes the effect of trees not tallied in the subplot but having a crown portion within it. If the two-dimensional representation of metric *D* exhibits a single local minimum that is at least one standard deviation from its mean across the search area, the coordinates of the cell center at the minimum are considered a trusted subplot match. The plot coordinates are computed from subplot matches, if any, provided that subplot arrangement approximates the FIA clustered design. Scripts were coded in C with parallelization support provided by the OpenMP library. Plot coordinates derived via matching were compared to those obtained by post-processed differential GPS (DGPS) with internally calibrated precision of 1.05 m.

RESULTS AND DISCUSSION

The root mean square discrepancy between production and DGPS coordinates was 8.86 m. At this (mis)registration level, the mean areal overlap between the actual and assumed subplot areas is only 28 percent. Sixty-six of the plots, over 80 percent, were registered within 2 m from the DGPS data. For more than half of those plots, all four subplots were registered. For six plots, the distance to DGPS references was between 2 and 5 m with all but one of them having just one subplot registered (Table 1).

Table 1.—Plot registration results

Distance to DGPS Coordinates (m)	Number of Plots (percent)	Mean of Per-plot Registered Subplots
<2	66 (80.5)	2.89
2-5	6 (7.3)	1.33
Unable to register	10 (12.2)	0.40

The process failed for 10 plots (12 percent) primarily because no trustworthy match could be found for any of the subplots, although in two cases matches were found but were rejected as incompatible with the FIA design. There were no false positive registrations.

The results indicate that the four subplots in the FIA design compensate for the limited areal extent of the individual subplot. The few crowns in most FIA subplots do not usually represent a unique tree arrangement within the search area but the cluster of four subplots allows the often many individual subplot matches to be filtered down to a single trusted matching solution for the plot. Because the majority of registration failures were associated with estimates of crown radius or shape substantially different from those observed in the LiDAR return cloud, assessing crown attributes via regional models might be a better choice than using generalized, national models. The weighting functions in Equation (1) quantify heterogeneity in the canopy and of openings that is apparent and prevalent in the study area. In such conditions, precisely registered plots can be used to assess the *f*, *w*, and *k* parameters and then used them to register other plots in the region. Parameter optimization will likely yield a pronounced local minimum in the distribution of metric *D* that can be automatically detected by using as threshold a moment in the distribution of *D*, such as the one standard deviation suggested. In the event that the crown and opening arrangement in one or more of the subplots is uncommon, plot registration can be achieved within search areas much larger than the one used in this study. However, where canopies exhibit uniformity and gaps are rare, as is typical in the Oregon temperate rainforest, consistent registration appears improbable. In such conditions, differences in canopy height and shape across the search area are comparable in magnitude to, if not smaller than, the discrepancies between real and modeled subplot crowns, and thus they rarely yield a unique and trusted matching solution. In open forests, canopy variability dominates imprecision in the modeled tree crowns, thereby allowing plot to be precisely registered.

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