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SÃO PAULO STATE UNIVERSITY (UNESP)
“JÚLIO DE MESQUITA FILHO”
FACULTY OF SCIENCE AND TECHNOLOGY

MATHEUS FERREIRA DA SILVA

Relaxation Labeling-Based Matching for Tree Point Cloud Registration

Presidente Prudente, SP
2025

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Relaxation Labeling-Based Matching for Tree Point Cloud Registration

Master’s Thesis presented to the Graduate Program in Cartographic Sciences (PPGCC) at São Paulo State University (UNESP), as part of the requirements for obtaining a master’s degree in Cartographic Sciences.

Supervisor: Prof. Dr. Maurício Galo
Co-Supervisor: Prof. Dr. Renato C. dos Santos

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IMPACTO[1] ESPERADO DESTA PESQUISA

Essa pesquisa propõe um método para o registro automático de nuvens de pontos geradas por sistemas LiDAR em ambientes florestais e agrícolas. O método proposto baseia-se na rotulação por relaxação, contribuindo para o mapeamento 3D, o monitoramento e a agricultura de precisão e alinha-se ao ODS 2 “Fome Zero e Agricultura Sustentável”.

POTENTIAL IMPACT OF THIS RESEARCH

This research proposes a method for the automatic registration of point clouds obtained by LiDAR systems in forest and agricultural environments. The proposed method is based on relaxation labeling and contributes to 3D mapping, monitoring, and precision agriculture, aligning with SDG 2, 'Zero Hunger and Sustainable Agriculture'.

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Abstract

The use of high-resolution LiDAR (Light Detection and Ranging) systems has become important in precision agriculture, supporting applications such as autonomous navigation, automated harvesting, yield estimation, and disease detection. Reliable three-dimensional (3D) data acquisition is essential for these tasks, and a key challenge lies in point cloud registration, which must align point clouds into a common coordinate system without relying on artificial targets or accurate external positioning. This Master's Thesis proposes an automatic registration pipeline designed for tree point cloud registration. First, individual tree stems are detected using a vertical continuity approach, from which trunk centers and diameter at breast height (DBH) are extracted as natural primitives for coarse registration. A relaxation labeling (RL) algorithm is then applied to establish correspondences between stem candidates from both point clouds based on attribute similarities and neighborhood compatibility. After establishing correspondences via RL, the coarse alignment is computed as a rigid-body transformation in 2D space, expressed in planimetric coordinates (*x, y*), followed by a vertical translation along the Z-axis estimated from local ground references of matched trees. Finally, refinement is performed using the Iterative Closest Point (ICP) algorithm, which adaptively adjusts the correspondence search radius based on the residuals from the coarse-stage alignment. The experiments were conducted using data acquired by a Terrestrial LASER Scanner (TLS) in two distinct areas: urban forest (A_1) and eucalyptus plantation forest (A_2). In A_1, the proposed method resulted in an average $RMSE_{3D}$ of 0.013 m, with errors mainly in the horizontal components (X, Y). In A_2, the $RMSE_{3D}$ increased to 0.033 m, mainly due to vertical discrepancies (Z) associated with terrain slope and insufficient ground sampling.

Keywords: Terrestrial LASER scanning (TLS). Precision agriculture. Tree detection. Iterative Closest Point (ICP).

Resumo

O uso de sistemas LiDAR (*Light Detection and Ranging*) de alta resolução tem se tornado cada vez mais relevante na agricultura de precisão, apoiando aplicações como navegação autônoma, colheita automatizada, estimativa de produtividade e detecção de doenças. Para essas aplicações, a aquisição confiável de dados tridimensionais (3D) é essencial, sendo o registro de nuvens de pontos um dos principais desafios, uma vez que requer o alinhamento das nuvens em um sistema de coordenadas comum sem a dependência de alvos artificiais ou de posicionamento externo preciso. Esta dissertação de mestrado propõe um processo automático para o registro de nuvens de pontos de árvores. Inicialmente, os fustes individuais são detectados por meio de uma abordagem de continuidade vertical, a partir da qual são extraídos os centros dos troncos e os diâmetros à altura do peito (DAP), utilizados como primitivas naturais para o registro aproximado. Em seguida, um algoritmo de Rotulação por Relaxação (*Relaxation Labeling* – RL) é aplicado para estabelecer correspondências entre candidatos de ambas as nuvens de pontos, com base na similaridade de atributos e na compatibilidade espacial de suas vizinhanças. Após a definição das correspondências pelo RL, o alinhamento aproximado é estimado por meio de uma transformação rígida em duas dimensões, no plano (*x, y*), seguida de uma translação vertical ao longo do eixo Z, estimada a partir de referências locais de terreno associadas às árvores correspondentes. Por fim, o refinamento do registro é realizado utilizando o algoritmo *Iterative Closest Point* (ICP), que ajusta de forma adaptativa o raio de busca por correspondências com base nos resíduos do alinhamento aproximado. Os experimentos foram conduzidos com dados obtidos por um escâner LASER terrestre (*Terrestrial LASER Scanner* – TLS) em duas áreas distintas: uma floresta urbana (A_1) e um plantio florestal de eucalipto (A_2). Na área A_1, o método proposto resultou em um $RMSE_{3D}$ médio de 0,013 m, com erros predominantemente associados às componentes horizontais (X, Y). Na área A_2, o $RMSE_{3D}$ aumentou para 0,033 m, principalmente devido a discrepâncias verticais (Z) decorrentes da inclinação do terreno e da amostragem insuficiente do solo.

Palavras-chave: Escaneamento LASER terrestre (TLS). Agricultura de precisão. Detecção de árvores. *Iterative Closest Point* (ICP).

List of Figures

List of Tables

Contents

Chapter 1

Introduction

The problem of point cloud registration has been extensively studied, and its investigation was substantially reinforced in the context of Simultaneous Location and Mapping (SLAM) research during the 1990s (Durrant-Whyte and Bailey, 2006). Over the years, the increasing demand for accurate geometric modeling of natural and built environments has driven further advancements in registration techniques for surface analysis and/or reconstruction (Weinmann and Jutzi, 2015; Witzmann et al., 2022; Benevides et al., 2024; Gonçalves et al., 2024; Liu et al., 2024). Point cloud registration plays a fundamental role in several applications, including mapping, object recognition, surface modeling, and multi-view reconstruction.

In agricultural and forestry environments, point clouds are generally obtained using LASER (Light Amplification by Stimulated Emission of Radiation) scanning technology or through reconstruction based on photogrammetric techniques. These data are used for multiple tasks, including tree inventory, canopy structure analysis, and growth monitoring (Gutiérrez et al., 2019; Cherubin et al., 2022; Rivera et al., 2023). However, the registration of point clouds acquired in these environments faces unique challenges due to the absence of man-made reference structures, which are frequently used as geometric anchors in indoor or urban settings (Shao et al., 2020; Ghorbani et al., 2022; Castanheiro et al., 2023; Wang et al., 2023).

In addition, key challenges encompass limited overlap between scans, vegetation obstruction, and confusion (ambiguity) arising from repetitive structures. These conditions reduce the effectiveness of traditional registration methods, particularly the Iterative Closest Point (ICP) algorithm and its probabilistic extensions, which are prone to convergence to incorrect local minima in cases of poor initial alignment or limited availability of distinctive geometric features (Brightman et al., 2023).

Although artificial targets can support point cloud registration, their deployment increases acquisition time and restricts scalability. An alternative is to use natural elements (e.g., tree stem positions) as key primitives for this task. When reliably extracted, these primitives provide spatial information that can be used to define correspondences based on geometric and topological constraints. Building on the aforementioned assumption, this Master's Thesis aims to explore the use of tree positions as primitives for terrestrial point cloud registration and to propose a method based on the relative spatial relationships among detected stems. The goal is to improve robustness during coarse alignment and provide a suitable initialization for fine registration using the ICP algorithm without relying on artificial markers.

1.1 Related Work

Point cloud registration in forest environments typically follows a coarse-to-fine strategy, in which an initial transformation is estimated based on geometric or semantic features, and subsequently refined using ICP algorithms. Recent studies have extended this framework by introducing more robust key point extraction techniques, stem-based matching strategies, and hierarchical feature representations specifically adapted to the structural characteristics of forest data (Kelbe et al., 2016; Tremblay et al., 2018; Guan et al., 2020; Dai et al., 2024; Wang et al., 2025).

Theiler et al. (2015) proposed a registration methodology that prioritizes geometric key point matching over descriptors, asserting that the latter are often insufficiently robust to significant viewpoint variation. Such viewpoint changes are an inherent consequence of terrestrial LASER scanning (TLS) acquisitions, which seek to minimize the number of scan stations. Their methodology uses K-4PCS, a RANSAC-based algorithm that operates on congruent sets of four points, to identify candidate transformations between key point sets. These sets are extracted using the 3D (three-dimensional) Harris and Difference of Gaussians. The findings indicate that, even in forested environments characterized by low overlap (approximately 40%), registration based on geometric matching can surpass descriptor-based methods, particularly under challenging conditions.

Hyyppä et al. (2021) introduced a two-dimensional coarse registration method that uses rotation- and translation-invariant local descriptors derived from tree locations. These feature descriptors represent the relative arrangements of surrounding stems and are compared using Euclidean distance in the feature space. The approach is suitable for large datasets, supporting up to 10,000 trees, and according to the authors, it is resilient to errors in tree detection and positioning.

Wang et al. (2023) introduced the *GlobalMatch* framework, which formulates forest point cloud registration as an inlier-grouping problem. By relying exclusively on stem positions, their approach eliminates the need for auxiliary attribute estimation. It also avoids the iterative trial-and-error paradigm commonly employed in RANSAC-based methods. In their algorithm, inliers are grouped in a single pass based on relative stem geometry, and the transformation is subsequently computed, yielding quadratic time complexity. The results confirm the robustness of spatial stem matching even in the absence of additional descriptors.

Chen et al. (2024) presented a clustering-based automated registration method for aligning UAV LiDAR (Unmanned Aerial Vehicle - Light Detection and Ranging) and TLS datasets. Their approach employs the DBSCAN (Density-Based Spatial Clustering of Applications with Noise) algorithm to divide the canopy into height-based layers, creating multi-level tree maps. Fast Point Feature Histograms (FPFH) are then computed for each cluster and matched between UAV LIDAR and TLS layers using Fast Global Registration. The best transformation is identified and subsequently refined using the ICP algorithm. Their results show that coarse alignment using stratified tree maps improves robustness to occlusions and point-density discrepancies.

Ghorbani et al. (2024) examined the registration of TLS and airborne LASER scanning (ALS) data by treating tree positions as stable primitives. Their method filters candidates based on the match diameter at breast height (DBH) and features from Principal Component Analysis (PCA). It matches tree locations using local triangulations to narrow the search space. Transformation parameters are estimated with Coherent Point Drift (CPD) and refined using the ICP algorithm. This hierarchical process achieves high accuracy even when registering TLS plots to ALS datasets covering up to 100 ha. Their results emphasize the importance of combining attribute filtering with spatial topology for robust alignment in large-scale forest environments.

These studies show a consistent preference in forest point cloud registration for using geometric primitives, such as stem positions, instead of relying on general 3D feature descriptors. This trend highlights the need to balance preprocessing requirements, such as terrain segmentation and attribute extraction, with robustness to occlusion and structural ambiguity.

The approach presented in this work follows a coarse-to-fine strategy. First, a 2D (two-dimensional) rigid-body transformation is obtained via relaxation labeling (RL), using stem positions and DBH to establish correspondences in the horizontal plane (X, Y). Subsequently, a vertical correction is applied by estimating a Z-axis shift based on the height difference between matched stems, thereby reducing vertical discrepancies between scans. Finally, the alignment is refined further using the ICP algorithm.

Unlike approaches that require intermediate structures, such as triangular irregular networks (TIN), the proposed method combines attribute-based similarity with spatial constraints derived from compatibility between local neighborhoods. Although initial attributes are not mandatory, they help reduce incorrect matches in structured environments such as plantations. Stem positions are extracted directly from the raw point cloud through a geometry-based detection approach that does not require segmentation or prior point cloud normalization (Da Silva et al., 2025; Dos Santos et al., 2024). This strategy is designed to address the limitations of descriptor-based methods in environments affected by occlusion, density variation, or morphological similarity among trees.

1.2 Motivation

Advances in photogrammetry and remote sensing technologies have underscored the utility of point cloud data for reconstructing different spaces, including forest and agricultural environments and extracting precise geometric information. LiDAR systems, now the state of the art for capturing 3D data, can be adapted to various platforms, providing high accuracy and operational efficiency. These systems surpass traditional methods, which, while effective at small scales, face challenges in time, spatial coverage, and efficiency when applied to larger areas. Nevertheless, in dense and irregular environments such as forests and agricultural fields, the acquisition and automatic generation of point clouds to comprehensively represent the scene pose significant challenges due to occlusions, object ambiguity, and variations in point density.

In this context, this work addresses the challenges of point cloud registration in unstructured environments by evaluating the hypothesis that, in scenarios characterized by repetitive and ambiguous elements, integrating attribute similarity and local neighborhood compatibility can improve the reliability of coarse alignment. Specifically, the application of relaxation labeling as a graph-based matching framework enables local compatibility constraints, contributing to more robust initial registration.

The relevance of this approach aligns with ongoing efforts of the international scientific community, including the ISPRS (International Society of Photogrammetry and Remote Sensing) Working Group II/2 (Point Cloud Generation and Processing), which emphasizes the development of automated methods for point cloud registration and fusion.

1.3 Objectives

The general objective of this work is to investigate the use of stem-based spatial matching for the registration of pairwise terrestrial point clouds in forest environments, employing a coarse-to-fine strategy based on relaxation labeling and ICP refinement. The specific objectives are:

- Introduce a relaxation labeling framework to establish correspondences between tree stems based on initial DBH estimates, Euclidean distance, and angular spatial compatibility.
- Propose an adaptive strategy for selecting the radius threshold in refinement using the ICP algorithm.
- Evaluate the proposed registration approach through qualitative and quantitative metrics, including the Root Mean Square Error (RMSE) on the centers of artificial sphere targets.

1.4 Research Structure

This Master's Thesis is organized into five chapters. Chapter 2 presents the theoretical background and related concepts. Chapter 3 describes the methodology used in this study, including the coarse-to-fine registration pipeline: stem extraction, relaxation-labeling matching, and blunder detection. Chapter 4 presents the experiments and evaluation results in urban and plantation forest scenarios. Finally, Chapter 5 discusses the findings, outlining potential directions for future work.

Chapter 5

Conclusion and Future Work

This Master's Thesis presents a coarse-to-fine registration approach for TLS point clouds in forest environments that combines relaxation labeling matching with ICP registration. Its main contribution is the adaptation and validation of an RL approach for matching point clouds using tree-center features extracted from TLS scans, followed by fine registration without artificial registration targets.

The experimental results demonstrated that relaxation-labeling-based matching is resilient to significant challenges in TLS point clouds, including ambiguity, low overlap, and limited geometry. When analyzing all possible scan pairs, the proposed method successfully identified at least three valid matches in nearly 70% of the combinations, even under conditions of weak geometry and low overlap.

The parameter sensitivity analysis revealed different behaviors between the urban and the plantation datasets. In the urban area, characterized by an irregular distribution of trees, relaxation labeling indicated to be robust to variations in parameters such as feature similarity and angular compatibility. Only the neighborhood size had a noticeable effect, confirming that distance-based compatibility was enough to model neighborhood relations in such environments.

In the plantation forest, where tree spacing is more regular, relaxation labeling showed greater sensitivity to parameter settings. Angular compatibility and DBH similarity were essential for establishing reliable matches, whereas increasing the neighborhood size raised the number of correspondences but reduced overall accuracy. These results emphasize the significance of attribute-based similarity and angular compatibilities in plantation environments.

The pairwise registration results also confirmed that the quality of the initial coarse alignment plays a key role in ICP refinement. In dataset A_1, the best accuracy was achieved for the pair with high overlap and similar viewpoints. Poorer results were associated with dispersed matches and high residuals in the X- and Y-components. In the A_2 dataset, the best results were supported by both high overlap and high match counts, whereas pairs involving stations at the edges of the acquisition network showed lower accuracy. Overall, the mean $RMSE_{3D}$ calculated with check sphere targets was approximately 0.013 m in A_1 and 0.033 m in A_2, indicating better performance in the urban scenario.

A decomposition of $RMSE_{3D}$ by component further showed that discrepancies in A_1 were influenced by the horizontal components (X and Y), whereas in A_2, they were mainly concentrated in the vertical component (Z). In A_1, errors stemmed primarily from opposing viewpoints and lateral displacement, whereas in A_2, they were exacerbated by terrain slope and insufficient ground sampling, particularly at edge stations.

The proposed method shows potential for application in other plantations with geometric characteristics similar to those of eucalyptus, such as rubber trees and pines. In addition, it can be explored using aerial datasets that support trunk sampling, as well as by integrating aerial and terrestrial point clouds.

5.1 Future Work

Although the results are promising, several directions remain open for improvement and further investigation:

- This work focused on pairwise registration, but in practice, TLS surveys involve multiple stations. Future work should integrate RL matching into global registration strategies, such as graph-based optimization (Choi et al., 2015), to reduce error propagation and improve edge-station registration.
- The parameter sensitivity observed in plantation environments suggests the need for automatic tuning strategies. Optimization-based methods could be developed to adjust RL parameters according to local scan geometry and forest structure. For example, metrics could be designed to adapt the neighborhood size, $k_{NN,}$ based on the spatial distribution of extracted features.
- The approach requires a more rigorous evaluation and comparison against widely adopted feature-matching methods for ambiguous environments, such as 4PCS (Theiler et al., 2015) and SIFT variants (Lowe, 2004).
- While this study used tree center position and DBH, future approaches could incorporate additional descriptors, such as local geometric features or higher-level tree attributes (e.g., crown height or shape). This may also enable multi-platform registration, for example, between UAV and TLS-derived point clouds.

- Errors in the Z component were associated with insufficient ground sampling on sloped terrain. Incorporating auxiliary ground modeling could mitigate this limitation, thereby improving the reliability of vertical alignment.
- Further validation is required in different forest types and crop contexts. The approach may also be adapted to other applications, such as fruit or leaf matching. In the work of Da Silva et al. (2024), oranges were extracted with position and radius as output features, which are similar to those used in this study. In such cases, the 2D matching logic can be extended to 3D by decomposing the problem across orthogonal planes (XY, YZ, and XZ).

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