博 士 論 文 の 内 容 の 要 旨
Abstract of Doctoral Dissertation

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論文題目 Dissertation Title	Subset focused rigid transformation search for registration of low overlapping 3D point clouds （重複の少ない３次元点群レジストレーションのための部分集合に着目した剛体変換探索）

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The advancement in computer hardware and the employment of 3D sensors has conveyed a wide range of applications and opportunities for development in image processing, resulting in new branches of research such as 3D image processing. One of the common types of data obtained from 3D sensors is the 3D point cloud, a collection of points in 3D space representing an object's or environment's shape. They are widely utilized in developing perception systems for self-driving cars, Autonomous Intelligent Vehicles, and Unmanned Aerial Vehicles. Also, in creating content for Virtual Reality experiences and Digital Twins.

The registration of 3D point clouds is a fundamental task in 3D image processing that looks for the transformation that optimally aligns the 3D point clouds to form a more extensive and detailed representation, being a core process for applications that need digital reconstruction. For example, autonomous intelligent vehicles perform System Localization and Mapping (SLAM), which estimates the vehicle's location and orientation while building a map of the environment comprised of hundreds or thousands of registered 3D point clouds obtained from a 3D sensor. Although there is a broad range of registration methods to date, only a few can successfully determine a good transformation that aligns 3D point clouds with partial overlaps below 40% - known as the low overlapping ratio.
The importance of developing registration methods for 3D point clouds with low overlap lies in the possibility of performing the full digital reconstruction of objects and environments with fewer data. Particularly useful in developing perception systems for truly robust Autonomous Intelligent Vehicles, which must perform SLAM without interruption in the presence of potentially low overlap 3D point clouds. Alternatively, it is desired when the storage resources or time to acquire the data are limited and compel us to obtain a few 3D point clouds from the most significant angles of an object or scene - having fewer 3D point clouds to work with to assemble an entire reconstruction.

The main reason why most typical registration approaches fail in a low overlap scenario is due to a high rate of incorrect data association (i.e., defining what points have to be aligned). The most common method to perform this data association is through a Nearest-neighbor search for each point in the point cloud to be aligned. However, it is an inadequate method when the 3D point clouds are initially far from the optimal alignment, or there are a lot of potential outliers coming from noise or not overlapping areas. Other registration approaches substitute the nearest-neighbor search for

pipelines making use of keypoints and feature point descriptors matched on the descriptive space and filtered by random sampling iterative methods. Nevertheless, these also fail in the low overlap conditions because the true overlap of low overlapping 3D point clouds lies between boundary surfaces and surfaces within the boundaries, which have very different point dispersion that governs the descriptiveness of the features, making them a challenge to associate correctly.
On the one hand, in recent years, Artificial Neural Networks have also been applied to perform the registration of 3D point clouds, bringing outstanding advancements to 3D image processing for digital reconstruction. Among them, some even focus on the low overlap problem. However, as with most Artificial Neural Network methods, these require extensive and costly datasets to train and high-end hardware to run due to the high computational complexity of convolving operations in 3D. On the other hand, the Hough transform is a well-known, conceptually simple, easy to implement, and flexible technique for feature extraction in image processing not fully explored in the 3D counterpart that does not require any training or high-end hardware to run. Furthermore, in 3D point cloud registration, these mechanisms allow us not to make direct hard point correspondences and drastically reduce the number of evaluation units to find the desired solution transformation.

This thesis presents the formulation details, implementations, experimental evaluations, and results of a couple of registration pipelines focused on aligning point subsets from the overlapping areas of 3D point clouds. The core idea of both methods relies on the likelihood of finding close to optimal transformations when aligning point subsets derived from the proper overlapping areas, regardless of the point dispersion. This work is divided into two parts to make it clear to the reader. The first part introduces the first developed method proposing the Supervoxel Segmentation technique to divide the 3D point clouds into subsets, registering them and evaluating the corresponding transformation via an inlier-focused error maximization objective function to find the best solution. The second part refers to the second developed method, which uses the same segmentation technique but improves the computational complexity by reducing the number of subsets to align. It implements a voting mechanism to determine the solution and replaces the evaluation of the transformations for the minimization of a metric that guarantees the maximum overlap and minimum error between corresponding points. The second part also covers a study on the effect of replacing the conventional quaternion rotation representation by the Euler angles over the pipeline of the second method. Furthermore, it extends to ablation and comparative studies that showcase how the method performs under its ruling parameters and compares it against the first method and other publicly available state-of-the-art methods.