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An adaptive approach for the reconstruction and modeling of as-built 3D pipelines from point clouds

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ABSTRACT

Automated extraction of 3D geometric shapes such as planes, spheres, cylinders, cones, and tori in laser-scanned point clouds is a challenging problem and a tedious process, especially when using cluttered data. This paper describes a modification of the existing Hough transform for the automatic detection of cylinder parameters in point clouds. Careful analysis reveals that the existing method still has excessive space and time complexity or yields imprecise outcomes. The approach described here modifies the orientation estimation with an area-based adaptive method that utilizes a small accumulator to detect significant peaks in the Hough space in the presence of single or multiple cylinders in the point cloud data. After orientation estimation, the position and radius are estimated using an orthonormal coordinate system with a circle fitting algorithm. These modifications are tested with extensive sets of real point cloud data, and experimental results show that the presented approach minimizes the space and time complexity. After detection, the relationship between cylinders is reconstructed to form a continuous axis network by tracking cylinder parameters obtained from earlier steps. Using the axis network of cylinders obtained from point clouds, models of entire pipelines that include straight pipes, elbow joints, and T-junctions are determinately defined, and output data is reconstructed in Smart Plant 3D (SP3D). The presented results show that the proposed approach indeed improves the computational complexity by reducing the space and time, and yields methods that can be employed in the automation of 3D pipeline model reconstruction.

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1. Introduction

Automatic extraction of geometric objects in laser-scanned point cloud data is an active area of recent research in the field of 3D reconstruction. Many applications require 3D models of objects to be extracted from laser-scanned data, including industrial plant design, reverse-engineering, and 3D visualizations. Projects involving monitoring, renovation, and maintenance also often require 3D models of objects extracted from laser-scanned data. Most of the equipment objects in industrial scenes are composed of basic geometric primitives such as planes, spheres, cylinders, cones, and tori [1–3]. As-built 3D pipelines are designed using cylinders, which is the most common geometric primitive object in the reconstruction of industrial plants, such as petrochemical and refinery plants (Fig. 1(a)).

Currently, there are numerous methods [1–2,6–9,12] that have parameterized and fitted cylinders with laser-scanned point cloud data. However, reconstruction of a fully automated 3D as-built pipeline model is an open challenge, as this process is typically laborious. Therefore, automatic detection and reconstruction of 3D models from laser-scanned point clouds in the industrial plant design field needs to be highly accurate and unambiguous. Industrial plants are constructed with widely varying items of connected equipment, and their relationship can be determined from the network of pipeline connection. For example, multiple connection relationships are possible between straight pipes, including T-junctions and elbow joints, and flanges. This connection relationship denotes the logical connectivity between the nearest neighboring elements of the piping equipment.

The two fundamental, well-known, approaches for detecting geometric shapes in 3D point cloud data are the Hough transform [4] and the RANdom SAmple Consensus (RANSAC) [5] method. Approaches based on the RANSAC method process the raw point cloud by using random sampling that requires a minimum number of data points to detect shapes. However, users need to set several thresholds that vary from model to model, especially when there is noisy data with outliers. This approach of accurately detecting 3D shapes (planes, spheres, cylinders, etc.) depends on the initial selection of points [3]. The other approach for detecting geometric shapes is to use methods that employ accumulation techniques, such as the Hough transform. The Hough transform carries out a voting procedure in the parameter space, and object candidates are obtained when they receive the highest number of votes.

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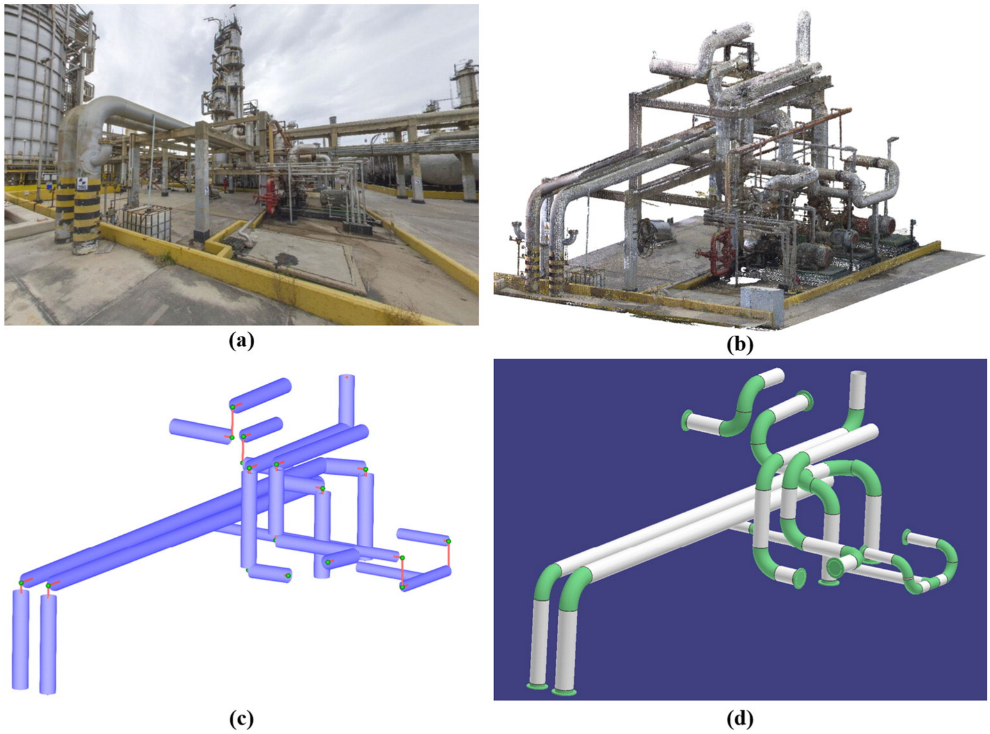

Fig. 1. Pipe plant reconstruction: (a) original plant, (b) laser-scanned point clouds, (c) cylinder detection and network reconstruction, (d) reconstructed pipelines in SP3D.

Methods based on the Hough transform have been successfully implemented to detect cylinders, planes, and spheres in laser-scanned point cloud data [9,16,25]. Hough transform methods generally have faster runtimes than RANSAC.

In this research, a modification of the sequential Hough transform [1] to detect cylinders in laser-scanned point cloud data is presented. To use a Hough transform to find cylinders, Rabbani et al. divided the problem into two steps. The first step estimates the cylinder axis direction while the second step estimates the position and radius using the estimated orientation from the first step. The aim of this research was to decrease the parameters from seven to only five by using spherical coordinates. A cylinder is represented by five parameters: (θ, ϕ) gives the orientation in spherical coordinates, r is the radius, and $P\,(u, v)$ is a point on the orientation axis, as shown in Fig. 2.

Therefore, the purpose of our research is to propose an adaptive method for detecting cylinder parameters and estimating the orientation of multiple cylinders simultaneously in laser-scanned point cloud data. The main contributions of this research are highlighted as follows:

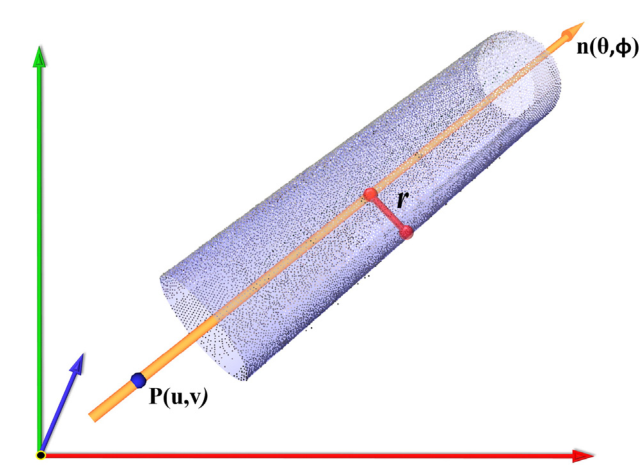

Fig. 2. The parameters for the cylinder.

1. An area-based adaptive Hough transform to estimate cylinder orientation.
2. Utilizing an area-based adaptive method to detect the universal direction in a Gaussian sphere to estimate the orientation of multiple cylinders simultaneously.
3. A modification of the existing approach by adopting a minimized number of computation steps for cylinder position and radius estimation using the algebraic circle fitting algorithm.
4. Reconstructing piping networks by finding the connection relationships between pipes.

The rest of this paper is organized into the following sections. Section 2 presents a literature review of the research relevant to object detection methods. In Section 3, the proposed methods, area-based adaptive Hough transform, multiple cylinder orientation estimation, and cylinder position and radius estimation, are presented. The experimental verification and results are presented in Sections 4, and 5 draws conclusions on the proposed method and outlines future work.

2. Literature review

The most popular techniques to detect geometric objects in laser-scanned point clouds are the Hough transform and RANSAC. This section discusses these methods and other various methods investigated to accelerate 3D object detection in laser-scanned point clouds.

In the field of digital image processing, the classical Hough-transform technique [4] is normally used to detect 2D straight lines using a parametric representation of the line in an image. This technique is most often used to detect straight lines, circles, and ellipses in 2D images [15]. With increased research into 3D point cloud reconstruction and modeling, the demand for detecting 3D geometric objects has also increased. In this context, the classical 2D Hough-transform has been extended to the extraction of 3D geometric objects like planes, spheres, and cylinders [10,20,25].

For any given input point cloud data, the Hough transform casts a vote for each point in the input point cloud to detect which points could possibly contain any geometrical object. The votes are accumulated over all samples and the detected features correspond to those with

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