Title:
Cylinder-based Efficient and Robust Registration and Model Fitting of Laser-scanned Point Clouds for As-built Modeling of Piping Systems

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Introduction:
Recently, the demand for a three-dimensional as-build modeling of plant piping systems based on a point cloud captured by a terrestrial laser scanner (TLS) has been increasing. To construct an as-built three-dimensional piping system model based on scanned data, a registration process is needed to align multiple point clouds including many cylindrical piping objects. The iterative closest point (ICP) [1] algorithm is frequently used for conducting the registration. However, in the case of capturing a cylindrical surface from different scanner positions, the point clouds tended to overlap only in portions with high laser beam incident angles. Therefore, they suffer from a large amount of noise and errors. Thus, the alignment result of ICP includes non-negligible errors or fails when the overlap between point clouds is small or absent. Moreover, since cylinder models are fitted to the registered point clouds, the registration error propagates to the model fitting error and results in an unacceptable accuracy degradation in the final as-built model.

Many marker-less registration methods have been proposed [2], [9] and [10]. However, they only aim at coarse registration and have to be followed through fine registration by ICP. Therefore, the conventional registration and model fitting of the scanned points of cylindrical surfaces can easily include registration error. In a previous report [7], we proposed a simultaneous cylinder-based registration and model fitting method for the as-build modeling of piping systems. The cylinder-based coarse registration method has also been proposed in the study [7]. This method does not necessarily require overlap between point clouds in the registration. The method could avoid the propagation of

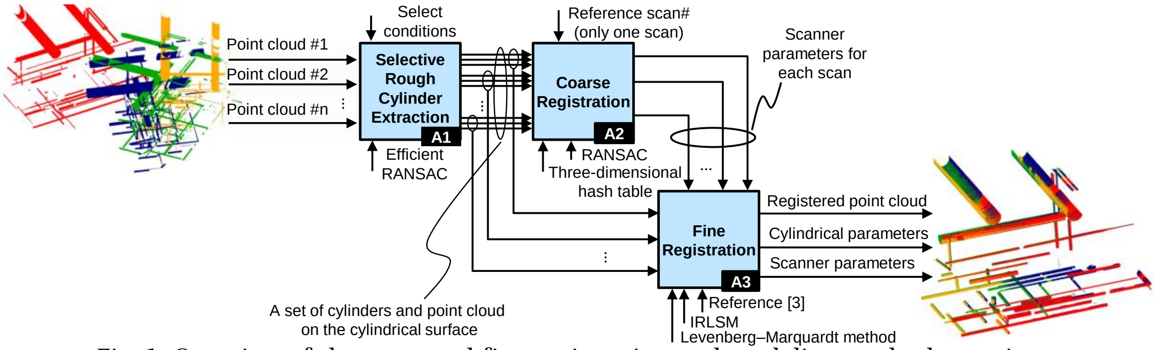

Fig. 1: Overview of the proposed fine registration and modeling method overview.

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errors from registration to cylinder fitting to achieve a highly accurate as-built modeling of piping systems. However, the registration and model fitting of [7] still has two drawbacks with regard to efficiency and robustness.

The first drawback concerns the excessively large point clouds measured on a large-scale piping system, which make coarse registration inefficient. The processing time of the coarse registration in [7] increased rapidly as the number of the extracted cylinders increased, e.g., 2.4 h with two scans and a few hundred cylinders. This inefficiency was because of the fact that many "fake" cylinders are mistakenly extracted and because the hash table not fully discriminating a corresponding cylinder pair in the coarse registration.

The second drawback is that the accuracy of registration and modeling sometimes decreases when it is applied to actual point clouds of complex piping systems in real environments. This inaccuracy is due to the non-negligible systematic error of scanned points appearing at large measurement distances and high incident angles. The presence of outlier points on the pipe, measured at T-junctions and flanges, are also the causes of this inaccuracy. The distribution of systematic error and outliers deviates substantially from the normal distribution. Additionally, our previous registration and model fitting using the least squares approach introduced some amount of error.

The objective of this study was to improve the efficiency and accuracy of our proposed cylinder-based registration and model fitting method for the as-built modeling of piping systems. As shown in Fig. 1, we first introduced a selective rough cylinder extraction in order to decrease the number of mistakenly extracted cylinders. Moreover, we devised a three-dimensional hash table for a considerably efficient coarse registration. Furthermore, we introduced the iteratively reweighted least squares method (IRLSM) in order to make the fine registration robust against systematic error and outliers. Finally, we evaluated the effectiveness of these improvements through scan simulation and as-built modeling using real point clouds captured from the piping system of a water treatment plant.

Efficient Coarse Scan Registration based on three-dimensional hash table

First, Efficient RANSAC [8] and PCA-based normal estimation were used to extract the fragments of cylindrical pipe surfaces and their supporting inlier points from the point clouds obtained by a single scan. Then, we selected only the plausible cylinder fragments for a more efficient and accurate registration.

After the selective rough cylinder extraction on each scan, the cylinders belonging to different scans and tending to correspond to each other were aligned in the coarse registration. The alignment was performed by the RANSAC approach and with the help of a hash table. In our previous study [7], we used a one-dimensional hash table, where the distance between cylinders was adopted as a hash key in order to avoid exhaustive searching for all cylinder pair combinations, and to determine the corresponding cylinders efficiently. However, in plants, many pipes are installed at equal distance from each other; therefore, the probability of key collision using only the distance has increased and the efficiency of the search for the corresponding cylinders remained low.

To solve the problem, we substituted the one-dimensional hash table with a three-dimensional hash table. As shown in Fig. 2, we constructed the three-dimensional hash table by following the steps outlined below: 1) the extracted cylinders from the point clouds of a single scan were classified into a set of *horizontal* C_H and *vertical* C_V cylinders based on their axis directions; 2) A pair of cylinders (c_m, c_n)

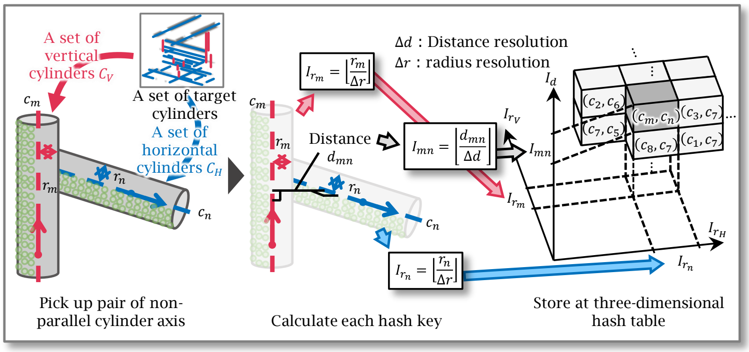

Fig. 2: Constructing a three-dimensional cylinder pair hash table.

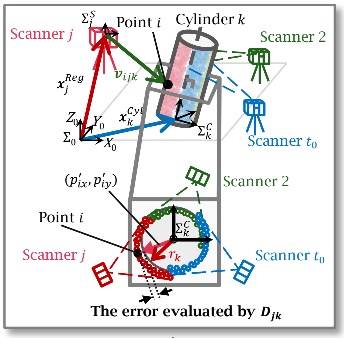

Fig. 3: Error function in the fine registration process.

was generated as $c_m \in C_V, c_n \in C_H$; 3) the distance $dist(c_m, c_n)$ between the c_m and c_n axes was converted into an integer index I_{mn} by applying quantization $I_{mn} = \lfloor dist(c_m, c_n)/\Delta d \rfloor$. Additionally, the radii r_m and r_n of c_m and c_n were also converted to integer indices as $I_{r_m} = \lfloor r_m/\Delta r \rfloor$ and $I_{r_n} = \lfloor r_n/\Delta r \rfloor$, where Δd and Δr are the distance and radius resolutions, respectively; 4) the cylinder pair (c_m, c_n) was stored into the entry indexed by $\left(I_{mn}, I_{r_m}, I_{r_n}\right)$ in the table.

Once the three-dimensional hash table was constructed, we could streamline the RANSAC-based coarse scan registration where the candidate for the corresponding cylinder pair in the other scan could be found in the entry with the same index. As a consensus, we evaluated the number of matched cylinders between different scans after the transformation. With consideration to efficiency, we performed a k-nearest neighbor search for the cylinder end point instead of performing a full search for the end points. The transformation with the maximum consensus was selected as the optimal alignment in the coarse registration.

<u>Cylinder-based Simultaneous Fine Scan Registration and Model Fitting based on IRLSM:</u>

Principle of simultaneous registration and model fitting

As shown in Fig. 3, the positional and geometric parameters of scanners and cylinders were calculated simultaneously by minimizing the distance error along the orthogonal direction from the point clouds to the analytic cylinder surfaces. This minimization can be formulated as follows:

$$\underset{\{\boldsymbol{x}_j^{Reg}\}\{\boldsymbol{x}_k^{Cyl}\}}{\text{minimize}} \Sigma_{j\in B-\{t_0\}}\Sigma_{k\in C}\Sigma_{i\in P_k} w\left(D_{jk}\left(i; \boldsymbol{x}_j^{Reg}, \boldsymbol{x}_k^{Cyl}\right)\right)\left[D_{jk}\left(i; \boldsymbol{x}_j^{Reg}, \boldsymbol{x}_k^{Cyl}\right)\right]^2 \tag{1}$$

where B is a set of scanners, t_0 is a scanner at a reference (fixed) location, and C is a set of uniquely identified cylinders in all scans $\{s^j\}$. P_k denotes a set of scanned points placed on cylinder k, and $\boldsymbol{x}_k^{Cyl}$ are the model parameters of cylinder k. $\boldsymbol{x}_j^{Reg}$ denotes the registration parameters of scanner j. $D_{jk}(i;\ \boldsymbol{x}_j^{Reg}$, $\boldsymbol{x}_k^{Cyl})$ denotes the fitting error function of scanned point i from cylinder k located at $\boldsymbol{x}_k^{Cyl}$, when a point i is captured by scanner j located at $\boldsymbol{x}_j^{Reg}$. $w(\quad)$ is the fitting weight at point i, and its selection will be discussed in the next section. This simultaneous adjustment of $\boldsymbol{x}_j^{Reg}$ and $\boldsymbol{x}_k^{Cyl}$ prevented the alignment error of the fine registration from propagating through the following model fitting, and helped preserve the modeling accuracy of the piping system.

The error function $D_{jk}(i)$ evaluated the squared orthogonal distance of a point from its corresponding cylindrical surface. To simplify the evaluation, we first classified the direction of the cylinder axis obtained from the course registration into one of three dominant orthogonal axial directions (X_0, Y_0 or Z_0) in the world coordinate system Σ_0, as has been proposed in [3]. For example, when the cylinder axis is nearly parallel to the Z_0 axis, the error function $D_{jk}(i)$ is defined by Eqs. (2) and (3):

$$D_{jk}\left(i;\ \boldsymbol{x}_j^{Reg}, \boldsymbol{x}_k^{Cyl}\right) = \sqrt{p_{ix}'^2 + p_{iy}'^2} - r_k \tag{2}$$

$$\boldsymbol{p}_i' = \mathrm{R}(\Phi_k)\mathrm{R}(\Omega_k)\,\{\boldsymbol{p}_i - \boldsymbol{q}_k\} \tag{3}$$

where $\boldsymbol{p}_i = \left[\, p_{ix}, p_{iy}, p_{iz} \,\right]^t$ and $\boldsymbol{p}_i' = \left[p_{ix}', p_{iy}', p_{iz}'\,\right]^t$ are the positions of a point i w.r.t. Σ_0 and a local coordinate system Σ_k^C fixed on cylinder k, with radius $r_k(\in \boldsymbol{x}_k^{Cyl})$, respectively. $\boldsymbol{q}_k = \left[\, q_{kx}, q_{ky}, 0 \,\right]^t(\in \boldsymbol{x}_k^{Cyl})$ is the intersection point between the cylinder axis and the X_0Y_0 plane w.r.t. Σ_0, $\mathrm{R}(\quad)$ is a 3 × 3 rotation matrix, and $\Omega_k(\in \boldsymbol{x}_k^{Cyl})$ and $\Phi_k(\in \boldsymbol{x}_k^{Cyl})$ are the rotational angles about the X_0 and Y_0 axis, respectively. Angles Ω_k and Φ_k specify the axial orientation of cylinder k. The cylinder axes nearly parallel to the X_0 or Y_0 axis are formulated in a similar manner.

The minimization problem of Eqn. (1) becomes nonlinear; however, we can derive the optimal solution of $\boldsymbol{x}_j^{Reg}$ and $\boldsymbol{x}_k^{Cyl}$ by starting from the initial values obtained from the coarse registration and by using the Levenberg-Marquardt method.

Optimization Process using Iteratively Reweighted Least Squares Method (IRLSM)

We introduce the IRLSM instead of the lease squares method (LSM) in order to solve the minimization problem expressed by Eqn. (1). The IRLSM is more robust against systematic error and outliers in comparison to the LSM, because a weight function depending on the error amount is assigned.

In this study, we tested the following three types of weight functions:

Fair: $$w(e_i) = 1/(1 + |e_i|/c) \tag{4}$$

Huber: $$w(e_i) = \begin{cases} 1 & |e_i| \le c \\ c/|e_i| & |e_i| > c \end{cases} \tag{5}$$

Tukey: $$w(e_i) = \begin{cases} [1 - (e_i/c)^2]^2 & |e_i| \le c \\ 0 & |e_i| > c \end{cases} \tag{6}$$

where c is the control parameter of each weight function. We adopted the residual error $D_{jk}(i)$ of the scanned point i as the weight variable e_i. The weight value of Eqn. (4) was halved if $e_i = c$. In the case of Eqn. (5), if $|e_i| \le c$, the weight value was 1. If $|e_i| > c$, then, the weight value decreased gradually depending on the value of c. However, the weight never converged to zero. On the other hand, Eqn. (6) decreased to zero if $|e_i| > c$, and was highly dependent on the initial values. However, the outlier was rejected completely. The accuracy of the IRLSM depended on correctly choosing the control parameter c. We adopted a normalized median absolute distribution about the median (MADN) [6] of $\{e_i\}$ as c. MADN is expressed by Eqs. (7) and (8), as follows:

$$\text{MADN}(\boldsymbol{e}) = \text{MAD}(\boldsymbol{e})/0.6745 \tag{7}$$

$$\text{MAD}(\boldsymbol{e}) = \text{MAD}(e_1, e_2, \ldots, e_n) = \text{Med}\{|\boldsymbol{e} - \text{Med}(\boldsymbol{e})|\} \tag{8}$$

The median absolute distribution about the median (MAD) was affected less by large outliers in comparison to the standard deviation because of using the median of $\{e_i\}$. Therefore, MADN could provide a robust estimator alternative to the standard deviation. The value of MADN decreased automatically because it was recalculated at each IRLSM iteration.

<u>Evaluation of Modeling Accuracies and Efficiencies:</u>

Modeling Accuracies of Point Clouds generated from Scan Simulation

We compared the modeling accuracy of cylinders of the proposed IRLSM-based method under different weight function settings to the accuracy achieved by ICP and our previous LSM-based approach [7]. First, we generated artificial point clouds from the CAD model of a piping system, where the Gaussian type measurement error was superimposed along the laser beam direction by using a scan simulation software. Three point clouds with a total of 5.65 million points were generated from three different scanner positions. The CAD model of the simple piping system ($10\,m \times 15\,m \times 8\,m$) shown in Fig. 4 was used. Then, the three point clouds were aligned by the proposed coarse registration method by using

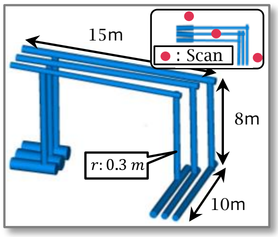

Fig. 4: CAD model of simple piping system.

	Condition											
	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Registration method	LSM	Free software	Commercial software	IRLSM using Eqn. (4)			IRLSM using Eqn. (5)			IRLSM using Eqn. (6)		
Modeling method		LS Fitting										
Control parameter c = MADN	-	-	-	× 1	× 3	× 6	× 1	× 3	× 6	× 1	× 3	× 6

Tab. 1: Fine Registration conditions and value of control parameters.

		Condition											
		I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Distance error E_d [mm]	Average	0.38	2.72	1.51	0.28	0.33	0.37	0.17	0.11	0.21	0.86	0.15	**0.04**
	Maximum	1.67	6.31	3.04	0.64	0.91	1.10	0.26	0.22	0.47	1.70	0.24	**0.06**
Angle error E_α [deg]	Average	0.021	0.080	0.047	0.004	0.006	0.008	0.001	0.002	0.006	0.005	**0.000**	0.001
	Maximum	0.037	0.239	0.110	0.008	0.013	0.018	**0.001**	0.006	0.014	0.011	**0.001**	**0.001**
Absolute value of radius error E_r [mm]	Average	0.49	0.48	0.66	0.10	0.13	0.15	0.07	0.08	0.12	0.12	0.07	**0.06**
	Maximum	1.89	1.62	2.20	0.32	0.49	0.62	0.15	0.23	0.54	0.26	0.15	**0.13**

Tab. 2: Average errors and maximum values of errors after fine registration (bold indicates best values).

10 manually-selected cylinders. Finally, fine registration and model fitting were performed under 12 different conditions as shown in Tab. 1. The fine registration of condition I was performed by our previous LSM-based registration and modeling method. The fine registration in condition II was executed by built-in ICP-based registration functions using freely available software [4], while a commercial software package was used for condition III [5]. For conditions II and III, least-squared fitting was used for modeling of the final cylinder. For conditions IV-VI, the proposed fine registration and modeling method using the IRLSM, which is expressed by Eqn. (4), were applied with different control parameter settings for the weight function ($1 \times \mathrm{MADN}, 3 \times \mathrm{MADN}$ and $6 \times \mathrm{MADN}$). Conditions VII-IX using the IRLSM expressed by Eqn. (5), and conditions X-XII using the IRLSM expressed by Eqn. (6), were applied with control parameters settings similar to those of conditions IV-VI.

Tab. 2 shows the distributions of distance error E_d, angle error E_α, and cylinder radius error E_r, between the two-cylinder axes after the fine registration. Their exact values were provided by the original CAD model. Methods I and IV-XII clearly obtained more accurate modeling results in comparison to the conventional ICP-based method (II and III). Especially, in condition XII, the error reduced to submillimeter order which was approximately one-tenth of the errors under conditions II and III. Therefore, condition XII achieved the best accuracy. The processing time under condition I was approximately 54 s, while that under condition XII was 142 s.

Finally, the relationship between the processing time and the number of input point clouds was investigated. For this purpose, the artificial scanned point clouds with different point-to-point interval settings were scanned using simulation software. The point-to-point interval was adjusted between 3 mm and 25 mm at 10m, as shown in Tab. 3. The proposed fine registration and modeling methods were used under condition I. As a result, the processing time linearly increased with the number of point clouds shown in Fig. 5. Moreover, even if the number of point clouds was not changed significantly, the processing time increased when the number of scanner positions and cylinders to be modeled increased because the processing time of minimization in Eqn. (1) is positively correlated with the number of variables.

The PtoP interval between the scanned points @10m [mm]	The number of points [Million points]
3.068	22.95
6.136	5.65
7.670	3.67
12.282	1.43
15.340	0.91
24.544	0.33

Tab. 3: Interval and number of points.

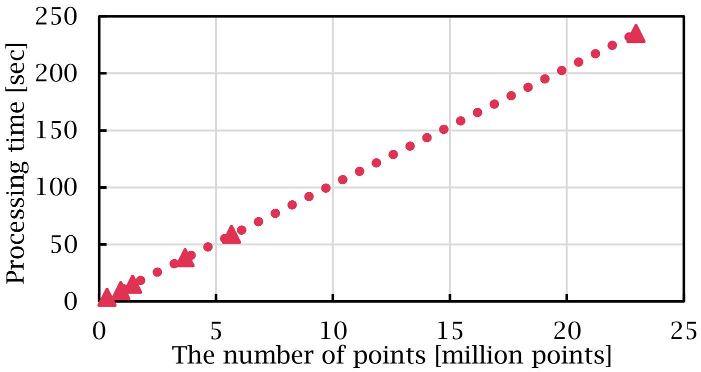

Fig. 5: Processing time at each interval.

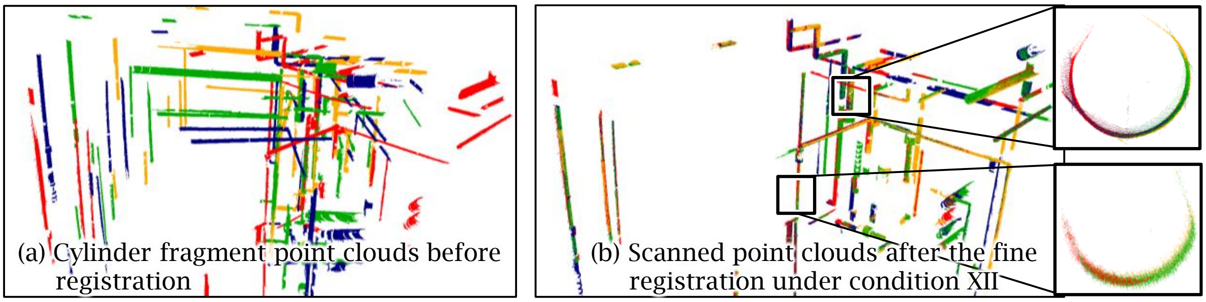

Fig. 6: Scanned point clouds before registration and after fine registration under condition XII. The red point cloud is a reference one, and the other point clouds are aligned to the red one.

Efficiencies for Real Point Clouds of Water Treatment Plant Piping System

Next, the proposed coarse method and fine registration method under condition XII were applied to real point clouds, and their efficiency was compared to that of the conventional method. The real point clouds of a real water treatment plant piping system($15m \times 10m \times 5m$), with a total of 1.70 million points, were captured by TLS (Faro Focus 3D) from four scanner positions. The selective rough cylinder extraction was applied to the point clouds of four scans in order to find approximately one hundred cylinder fragments in each scan, as shown in Fig. 6(a). The point clouds were then aligned by the coarse registration. The coarse registration with the one-dimensional hash table [7] took 9 min, while the three-dimensional hash table only took 0.5 min. The maximum number hash key collisions also decreased from 927 to 158. Moreover, the proposed IRSLM-based fine registration and modeling under condition XII were applied to the point cloud after coarse registration in order to obtain the final result shown in Fig. 6(b). The fine registration and modeling under condition XII took 12 min. As shown in Fig. 6(b), visual inspection confirmed that the fine registration was successfully completed.

Conclusions:

The efficiency and accuracy of the simultaneous cylinder-based registration and model fitting method was improved with regard to the as-built modeling of piping systems. A three-dimensional hash table was introduced to the coarse registration. The IRLSM-based fine registration and model fitting method were robust against systematic error and outliers. The simulations results obtained in this study confirmed that the modeling accuracy achieved by the proposed IRLSM-based approach clearly outperformed the previous LSM-based and ICP-based approaches with regard to modeling accuracy. In a real environment, the three-dimensional hash table achieved a significantly efficient coarse registration.

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