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Latent Reference Patterns for Geometric Drift Detection in the Printing Process

Diana Bratić
Denis Jurečić
Suzana Pasanec Preprotić
Gorana Petković

University of Zagreb,
Faculty of Graphic Arts,
Zagreb, Croatia

ABSTRACT

Geometric drift in the printing process can alter the position and orientation of graphic elements, degrading print quality and reducing the reliability of print inspection. Timely detection of such deviations is essential for maintaining process stability and ensuring consistent product quality. This study investigates latent reference patterns for detecting translational and rotational drift. The objective was to determine whether a non-periodic spatial arrangement of reference elements can reliably estimate pattern position and orientation and serve as a reference structure for geometric drift detection. Latent reference patterns were generated as binary point structures using Bridson's Poisson disk sampling algorithm. Poisson disk sampling was selected to produce a non-periodic spatial configuration with a controlled minimum separation distance between reference elements, reducing the likelihood of ambiguous geometric correspondences during geometric registration. The centers of the circular reference elements were generated pseudo-randomly subject to a predefined minimum separation distance, while the domain dimensions and generation parameters remained constant, making the spatial arrangement of the reference elements the only variable. Two-dimensional rigid geometric transformations were applied to the generated patterns. Translation was modeled by displacement components Δx and Δy, each varied from −10 px to +10 px in 1 px increments, while rotation was modeled by a rotation matrix about the pattern center over the range from −5° to +5° in 0.5° increments. A transformed latent reference pattern was generated for each translation-rotation combination, forming a dataset of simulated geometric deviations. The original and transformed configurations were compared by estimating the translation and rotation that produce optimal geometric alignment of the corresponding reference elements through minimization of the mean squared coordinate error. The estimated transformation parameters were compared with the prescribed values, and absolute estimation errors were calculated. The results demonstrated that the non-periodic spatial configuration of the latent reference pattern enables reliable estimation of translational and rotational drift within the investigated transformation range. These findings support the use of latent reference patterns as reference structures for developing automated geometric drift detection methods under simulated geometric conditions relevant to the printing process.

KEY WORDS

Geometric drift, latent reference patterns, Poisson disk sampling, geometric registration, printing process

1. Introduction

Geometric stability of the printed image is an important factor in maintaining consistent print process quality. Changes in the position and orientation of graphic elements can cause register deviations, alter their relative positions, and affect the reliability of automated quality inspection. Such deviations can occur at different stages of reproduction, and their characteristics depend on the printing technology used. In electrophotographic printing, individual devices have been shown to introduce characteristic geometric distortions during reproduction that can be extracted from the printed image and used as a geometric signature of the device (Bulan, 2009). In continuous roll-to-roll processes, register deviations are also associated with the dynamics of substrate transport and changes in material speed and tension, making their detection and compensation important for process control (Chen, Shan & Zhang, 2025).

The development of machine vision systems has enabled quantitative measurement of geometric deviations based on the positions of elements extracted from captured images. In printed electronics, methods for determining register errors have been developed that combine image processing, edge detection of control marks, and mathematical estimation of their positions. These methods have enabled register deviations to be determined with subpixel accuracy (Zhang et al., 2024). Models have also been developed for roll-to-roll printing systems that relate printing and material transport parameters to the occurrence of register errors (Gafurov et al., 2024). Regardless of the detection method used, determining geometric changes requires a reference structure against which changes in position can be measured.

Geometric drift detection can be considered as a registration problem between two geometric configurations. Registration is the process of spatially aligning different representations of the same structure and is applied in various areas of image processing and computer vision (Cocianu, Uscatu & Stan, 2023). In point set registration, a spatial transformation is determined to align one set of coordinates with another, with point correspondence and transformation parameter estimation representing the main components of the procedure (Pei et al., 2023). In a rigid two-dimensional transformation, the geometric relationships within the configuration remain unchanged, while its position and orientation change. Such a change can be described by horizontal and vertical translation and rotation.

By using a larger number of spatially distributed reference elements, geometric information was not limited to the position of a single registration mark but was contained in the configuration as a whole. Spatial relationships between points have been used in point set registration methods to determine the alignment between different configurations (de Sousa & Kropatsch, 2015; Pei et al., 2023). On this basis, Poisson disk sampling was applied in this study to generate a non-periodic reference structure whose position and orientation could be tracked based on the coordinates of its elements.

Such a structure was considered as a latent geometric reference that differed from a single registration mark. Information about the geometric state was distributed across multiple elements that together formed a non-periodic spatial configuration. Changes in the position and orientation of the structure could therefore be determined by comparing the original and transformed configurations. This enabled the evaluation of a non-periodic pattern as a reference structure for determining rigid geometric drift.

The basic case of this approach was investigated under controlled simulation conditions. The reference pattern was generated as a binary structure of circular elements whose centers were pseudo-randomly distributed using Poisson disk sampling with a defined minimum separation distance. Known horizontal and vertical translations ranging from −10 to +10 pixels were applied to the original configuration in one-pixel increments. Rotation about the pattern center was applied over the range from −5° to +5° in 0.5° increments. For each combination of transformation parameters, translation and rotation were estimated, and the estimated values were then compared with the prescribed values.

The objective of this study was to determine whether a non-periodic latent reference pattern generated using Poisson disk sampling could enable reliable estimation of translational and rotational drift within the defined transformation range. The study was limited to rigid transformations and controlled simulation conditions to investigate the geometric basis of the proposed approach without the influence of additional image degradation and more complex geometric deformations.

The working hypothesis was that a non-periodic spatial configuration of reference elements generated with a controlled minimum separation distance contains sufficient geometric information for reliable estimation of translational and rotational drift within the defined transformation range.

2. Methodology

The study was conducted as a controlled computational experiment to investigate the use of a non-periodic latent reference structure for estimating rigid geometric drift. The use of predefined input parameters enabled systematic evaluation of the simulation model under controlled conditions (Kleijnen, 2008). The procedure included generation of the original reference pattern,

application of known translational and rotational transformations, estimation of the transformation parameters, and comparison of the estimated and prescribed values.

The reference pattern generation parameters were kept constant throughout the experiment, while the rigid transformation parameters were systematically varied. This enabled direct evaluation of the accuracy of translation and rotation estimation under controlled simulation conditions.

2.1. Generation of the latent reference pattern

The latent reference pattern was generated as a two-dimensional non-periodic configuration of circular elements. The positions of their centers were determined using Bridson's Poisson disk sampling algorithm (Bridson, 2007). The pattern was generated within a rectangular domain of defined dimensions, with a predefined minimum distance between the centers of neighboring elements.

The set of image centers of the reference elements was defined as:

$$P = \left\{ \mathbf{p}_i = \begin{bmatrix} x_i \\ y_i \end{bmatrix}, \quad i = 1, \dots, N \right\} \tag{1}$$

where x_i and y_i are the coordinates of the center of the i-th reference element, and N is the total number of elements in the pattern.

The minimum allowed distance between any two different centers was defined by the following condition:

$$\left\| \mathbf{p}_i - \mathbf{p}_j \right\|_2 \geq d_{\min}, \qquad i \neq j \tag{2}$$

where d_{min} is the minimum Euclidean distance between the centers of the reference elements. This constraint prevented local clustering while maintaining a non-periodic spatial distribution.

After the coordinates were determined, a circular element of equal size was placed at each position, resulting in a binary reference pattern. The domain dimensions, minimum distance between centers, size of the circular elements, and other generation parameters were kept constant throughout the experiment.

This ensured that only the parameters of the applied geometric transformation varied between individual test cases.

2.2. Modeling of translational and rotational drift

A two-dimensional rigid transformation consisting of translation and rotation was applied to the original configuration. Translation was defined independently in the horizontal and vertical directions. The translation values Δx and Δy were varied from −10 to +10 pixels in one-pixel increments.

The translation vector was defined as:

$$\mathbf{t} = \begin{bmatrix} \Delta x \\ \Delta y \end{bmatrix} \tag{3}$$

Rotation was performed about the geometric center of the reference pattern domain. The rotation angle θ was varied from −5° to +5° in 0.5° increments. The two-dimensional rotation matrix was defined as:

$$\mathbf{R}(\theta) = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \tag{4}$$

The transformation was performed about the center of the pattern to ensure that the change in orientation did not simultaneously introduce a displacement resulting from rotation about the origin of the coordinate system. The transformed position of the i-th reference element was determined by the following expression:

$$\mathbf{q}_i = \mathbf{R}(\theta)(\mathbf{p}_i - \mathbf{c}) + \mathbf{c} + \mathbf{t} \tag{5}$$

where p_i is the original position of the reference element, q_i is its transformed position, c is the center of the pattern, R(θ) is the rotation matrix, and t is the translation vector.

For each horizontal translation value, all vertical translation and rotation values were applied. For Δx and Δy, 21 values were obtained for each parameter, while 21 values were also obtained for the rotation angle.

The total number of tested combinations of transformation parameters was:

$$N_T = 21 \times 21 \times 21 = 9261 \tag{6}$$

For each of the 9261 combinations, a transformed configuration of reference elements was obtained with known values of horizontal and vertical translation and rotation angle.

2.3. Estimation of rigid transformation parameters

The rigid transformation parameters were estimated by comparing the coordinates of the original and transformed configurations. Since the data were generated synthetically, the identity of individual reference elements was preserved after transformation. The correspondences between the original and transformed points were therefore known, allowing the analysis to focus on the estimation of the rigid transformation parameters.

For a given pair of original and transformed configurations, the transformation that provided the best alignment of the corresponding reference points was determined. The mean squared coordinate error was used as the alignment criterion. For arbitrary values of the rotation angle θ and translation vector t, the error function was defined as:

$$E(\theta, \mathbf{t}) = \frac{1}{N}\sum_{i=1}^{N} \|\mathbf{q}_i - [\mathbf{R}(\theta)(\mathbf{p}_i - \mathbf{c}) + \mathbf{c} + \mathbf{t}]\|_2^2 \quad (7)$$

The value of the function E represented the mean squared deviation between the actual positions of the transformed points and the positions obtained for the considered rigid transformation parameters. The estimated parameters were determined as the values at which this function was minimized:

$$(\hat{\theta}, \hat{\mathbf{t}}) = \arg\min_{\theta, \mathbf{t}} E(\theta, \mathbf{t}) \quad (8)$$

where θ̂ and t̂ are the estimated rotation angle and translation vector.

The minimization was not performed by iterative searching of the transformation parameter space, but by using a closed-form solution to the rigid alignment problem for corresponding point sets (Chen et al., 2024).

After centering the original and transformed configurations, a cross-covariance matrix was formed, and singular value decomposition (SVD) was performed. The optimal rotation matrix was determined from the resulting matrices, and the estimated rotation angle was calculated from this matrix. Translation was then determined from the difference between the centroids, taking the estimated rotation into account. In this way, the estimated values of $(\Delta x)\hat{}$, $(\Delta y)\hat{}$ and $\theta\hat{}$ that minimized the coordinate error between the corresponding reference elements were obtained directly for each transformed configuration.

This formulation enabled direct comparison of the estimated rigid transformation parameters with the parameters previously used to generate the transformed configuration.

2.4. Evaluation of estimation accuracy

Estimation accuracy was evaluated by comparing the estimated parameters with the known values of the applied transformation. For each of the 9261 transformations, the estimation errors for horizontal translation, vertical translation, and rotation angle were determined separately.

The absolute error of horizontal translation was determined as:

$$e_x = \left|\widehat{\Delta x} - \Delta x\right| \quad (9)$$

where $(\Delta x)\hat{}$ is the estimated value and Δx is the prescribed value of horizontal translation.

The absolute error of vertical translation was determined as:

$$e_y = \left|\widehat{\Delta y} - \Delta y\right| \quad (10)$$

where $(\Delta y)\hat{}$ is the estimated value and Δy is the prescribed value of vertical translation.

The absolute error of the rotation angle was determined as:

$$e_\theta = \left|\hat{\theta} - \theta\right| \quad (11)$$

where $\theta\hat{}$ is the estimated rotation angle and θ is the prescribed rotation angle.

In addition to the separate errors of the horizontal and vertical components, the total translation error was determined as the Euclidean distance between the prescribed and estimated translation vectors:

$$e_t = \sqrt{\left(\widehat{\Delta x} - \Delta x\right)^2 + \left(\widehat{\Delta y} - \Delta y\right)^2} \quad (12)$$

The obtained errors were analyzed across the entire set of transformations to determine the estimation accuracy within the investigated translation and rotation ranges. The results were also compared with respect to the magnitude of the prescribed displacement to determine whether the estimation error depended on the position within the investigated transformation space.

2.5. Computational implementation

The generation of the reference pattern, application of rigid transformations, estimation of transformation parameters, and error analysis were performed using Python 3.12.14. NumPy 2.3.5 was used for numerical operations, coordinate processing, and matrix calculations, including singular value decomposition. Pandas 2.2.3 was used to organize and store the results, while Matplotlib 3.10.8 was used for graphical presentation of the results (Dey, 2018).

A fixed random number generator seed (seed = 20261003) was used to generate the pseudo-random spatial configuration, ensuring reproducibility of the generated reference pattern.

For each investigated transformation, the prescribed values of Δx, Δy and θ, their estimated values, and

the corresponding errors were stored. This produced a single dataset that was used for statistical analysis and graphical presentation of the results.

3. Results

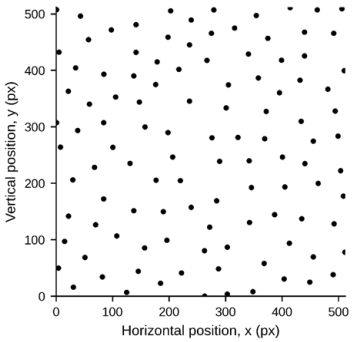
The simulation investigated the possibility of estimating rigid geometric drift parameters using a non-periodic latent reference pattern. The generated spatial arrangement of reference elements was analyzed, and the prescribed and estimated transformation parameters were compared for all defined combinations of horizontal translation, vertical translation, and rotation. Estimation accuracy was evaluated separately for the individual transformation components and for the total translational drift.

A total of 9261 combinations of rigid transformations were analyzed. This covered the entire defined transformation parameter space, including 21 values of horizontal translation, 21 values of vertical translation, and 21 values of the rotation angle. The results were analyzed using all simulated combinations, without subsequent selection or exclusion of individual cases.

3.1. Generated latent reference pattern

Poisson disk sampling was used to generate a non-periodic spatial configuration within a reference domain of 512 × 512 pixels. The minimum allowed distance between the centers of the elements was 40 pixels. With the defined generation parameters, 110 reference elements were obtained.

The spatial arrangement of the elements is shown in Figure 1. The generated configuration did not contain a regularly repeating spatial unit. At the same time, the minimum distance constraint between the centers prevented overlap and pronounced local clustering of the elements.



» **Figure 1:** *Non-periodic latent reference pattern generated using Poisson disk sampling*

Since the same reference pattern was used throughout the experiment, the spatial configuration did not represent an additional variable between individual transformations.

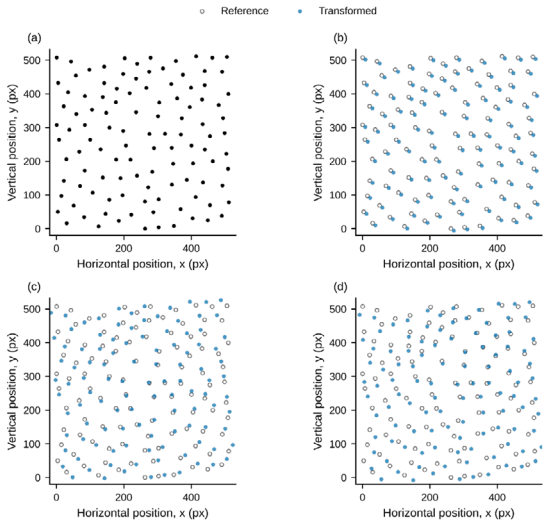
The resulting configuration provided a spatially distributed set of reference elements across the image domain, allowing the geometric state of the pattern to be represented by the configuration as a whole.

3.2. Application of rigid geometric transformations

Horizontal translation Δx, vertical translation Δy, and rotation θ about the center of the reference pattern were applied to the original configuration. Both translation components were varied independently from −10 to +10 pixels in one-pixel increments, while the rotation angle was varied from −5° to +5° in 0.5° increments.

By fully combining the prescribed values, a grid of 21 × 21 × 21, corresponding to 9261 transformations, was obtained. In this way, each horizontal translation value was tested in combination with all vertical translation and rotation values, and the same principle was applied to the remaining parameters.

Figure 2 shows representative examples of the original configuration and the translational, rotational, and combined transformations. The figure was generated from the actual coordinates used in the simulation rather than from a separately created schematic illustration. The geometric relationships between the elements were preserved in the transformed configurations because rigid transformations were applied.



» **Figure 2:** *Representative examples of rigid transformations of the latent reference pattern*

The original configuration (a), translation with $\Delta x = 8$ px and $\Delta y = -6$ px (b), rotation with $\theta = 4°$ (c), and their combination (d) are shown.

The transformed configurations preserved the relative spatial arrangement of the reference elements, while their position and orientation changed according to the prescribed transformation parameters. These examples illustrate the geometric deviations subsequently used to evaluate the estimation of translational and rotational drift.

3.3. Estimation of translational drift

The estimated values of horizontal and vertical translation were compared with the corresponding prescribed values for all 9261 transformations. Across the entire investigated range, the prescribed and estimated translation parameters showed nearly complete agreement.

For horizontal translation, the mean absolute error was 4.917×10^{-15} px, while the RMSE was 6.189×10^{-15} px. The maximum recorded absolute error of the horizontal component was 2.309×10^{-14} px. The median absolute error was 4.219×10^{-15} px.

For vertical translation, the mean absolute error was 5.933×10^{-15} px, and the RMSE was 7.428×10^{-15} px.

The maximum absolute error was 1.954×10^{-14} px, while the median was 5.329×10^{-15} px.

When the horizontal and vertical components were considered together as the total translation vector error, the mean error was 8.542×10^{-15} px. The RMSE was 9.668×10^{-15} px, and the maximum recorded value was 2.474×10^{-14} px. In 95% of the analyzed transformations, the total translation error did not exceed 1.685×10^{-14} px.

The obtained values were several orders of magnitude smaller than one pixel. The horizontal and vertical components showed the same order of error magnitude, indicating comparable estimation accuracy in both translation directions. Considering the simulation procedure, these deviations represented the numerical precision of the calculations rather than a measurable error in determining the position of the reference pattern.

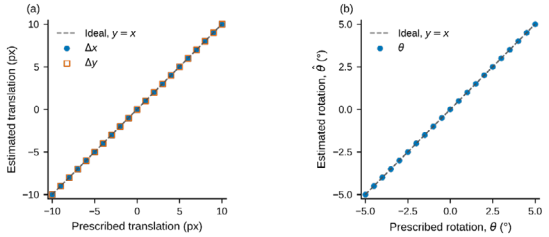
3.4. Estimation of rotational drift

The estimated rotation angle values were also compared with the prescribed values across the entire range from −5° to +5°. As with the translation components, the estimated angles agreed with the prescribed values within the numerical precision of the computational procedure.

The mean absolute error of rotation estimation was $5.973 \times 10^{-15}°$, while the RMSE was $7.329 \times 10^{-15}°$. The median absolute error was $5.773 \times 10^{-15}°$, and the maximum recorded deviation was $1.665 \times 10^{-14}°$. In 95% of the analyzed transformations, the absolute rotation error was less than or equal to $1.332 \times 10^{-14}°$.

No systematic increase in rotation error was observed toward the limits of the rotation range investigated. The estimation accuracy therefore remained comparable across both negative and positive rotation angles within the investigated range.

A comparison of the prescribed and estimated values of the translation components and rotation is shown in Figure 3. Horizontal and vertical translation are shown together, while rotation is shown separately. The estimated values agreed with the ideal relationship y = x, and the numerical deviations were not visually distinguishable at the scale shown.



» **Figure 3:** *Comparison of prescribed and estimated rigid transformation parameters*

Figure 3a shows horizontal and vertical translation, while Figure 3b shows rotation, with the dashed diagonal indicating the ideal relationship between the prescribed and estimated values.

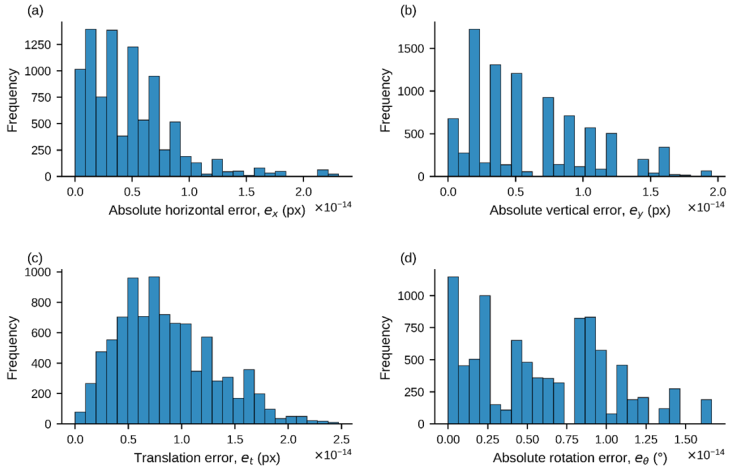
3.5. Analysis of estimation errors

Since the deviations between the prescribed and estimated parameters could not be distinguished in the direct comparison plots, the distribution of absolute errors was additionally analyzed. The results showed that all analyzed errors remained approximately within the range of 10^{-15} to 10^{-14} in the corresponding units.

The magnitude of these errors remained consistent with floating-point numerical precision across the investigated transformation parameter space. No individual transformation produced an error outside the numerical magnitude observed for the complete dataset.

The error distributions for the individual components of the rigid transformation are shown in Figure 4.

For horizontal translation (a), vertical translation (b), and total translational drift (c), the errors remained at approximately 10^{-14} px, while for rotation (d), the



» **Figure 4:** *Distribution of absolute errors in rigid transformation parameter estimation*

maximum deviation remained at approximately 10^{-14}°. Summary error metrics are presented in Table 1.

Table 1

Error metrics for rigid transformation parameter estimation

Parameter	MAE	RMSE	Maximum absolute error	95th percentile
Horizontal translation	4.917 × 10^{-15} px	6.189 × 10^{-15} px	2.309 × 10^{-14} px	1.243 × 10^{-14} px
Vertical translation	5.933 × 10^{-15} px	7.428 × 10^{-15} px	1.954 × 10^{-14} px	1.510 × 10^{-14} px
Total translation	8.542 × 10^{-15} px	9.668 × 10^{-15} px	2.474 × 10^{-14} px	1.685 × 10^{-14} px
Rotation	5.973 × 10^{-15}°	7.329 × 10^{-15}°	1.665 × 10^{-14}°	1.332 × 10^{-14}°

The obtained results showed that, for the non-periodic configuration used, it was possible to reconstruct the prescribed rigid transformation parameters across the entire investigated range of translations and rotations. Under idealized simulation conditions, no practically significant estimation error was observed. The remaining deviations corresponded to the numerical precision of the computational procedure.

4. Discussion

The study investigated the applicability of a non-periodic latent reference pattern for determining rigid geometric drift under controlled simulation conditions. The obtained results showed that the prescribed values of horizontal and vertical translation and rotation could be reconstructed across the entire investigated transformation range. For all 9261 analyzed combinations, the deviations between the prescribed and estimated values remained at the level of the numerical precision of the computational procedure.

This result should be considered in the context of the conditions under which the experiment was conducted. The transformations were applied directly to the coordinates of the reference elements, and the correspondences between the elements of the original and transformed configurations were known.

Therefore, errors on the order of 10^{-14} px for translation and 10^{-14}° for rotation did not represent the estimated accuracy that could be expected in an actual printing process. Instead, they showed that no practically significant error occurred in determining the rigid transformation within the defined mathematical model. A similar principle of evaluating registration methods using known artificially generated transformations has also been applied in previous studies of point set and image registration (Fu, Chen & Wang, 2022; Alba et al., 2015).

The results also showed that the spatial configuration of 110 reference elements contained sufficient geometric information to determine the three investigated rigid transformation parameters. Point set registration is based on determining the spatial transformation between two configurations, with point correspondence and transformation parameter estimation representing the fundamental components of the procedure (Pei et al., 2023). In this study, the latter part of the problem was considered separately from the problem of determining correspondences. Because the identity of the points was known, the results therefore confirm the possibility of estimating transformation parameters from a non-periodic configuration, but do not allow conclusions to be drawn about the effectiveness of automatically establishing correspondences between elements.

The use of Poisson disk sampling enabled the generation of a non-periodic configuration with a controlled minimum distance between elements. This type of spatial distribution has been used in various geometric data processing procedures because it enables control of local density and distances between points (Wei, 2008; Jiao et al., 2024; Comino-Trinidad, Chica & Andújar, 2023). No comparison with periodic or other non-periodic configurations was performed in this study. Therefore, the obtained results do not support the conclusion that the Poisson disk arrangement provided greater registration accuracy than other possible spatial arrangements. They only demonstrate that the investigated Poisson disk configuration enabled unambiguous estimation of the prescribed rigid transformations within the applied simulation model.

The obtained results represented the basic geometric case of drift detection. In actual machine vision systems, the positions of reference elements are determined from captured images, and the estimation may therefore be affected by image resolution, the element detection procedure, and other sources of deviation. Previous studies of registration systems in printing processes have shown that geometric deviations can be determined through image processing and analysis of the positions of control marks (Zhang et al., 2024), while in roll-to-roll processes, registration deviations are also associated with the dynamic parameters of the process and substrate transport (Chen, Shan & Zhang, 2025; Gafurov et al., 2024). These effects were not investigated in this study.

The limitations of the study therefore arose primarily from the idealized simulation model. Image degradation, errors in determining the centers of the reference elements, unknown correspondences, and nonlinear geometric deformations were not included. In addition, only one generated spatial configuration was investigated using constant Poisson disk sampling parameters. Therefore, the results did not represent an assessment of the robustness of the proposed approach under actual printing conditions, but rather a verification of its basic geometric feasibility.

Despite these limitations, the obtained result provided a basis for further investigation of latent reference structures. It was confirmed that the position and orientation of the investigated non-periodic configuration could be determined from the coordinates of its elements without practically significant error under idealized simulation conditions. Future research should progressively incorporate sources of deviation characteristic of the detection procedure and the printing process and investigate the behavior of the reference structure when correspondences between elements are not known in advance.

5. Conclusion

The study investigated the use of a non-periodic latent reference pattern generated using Poisson disk sampling for determining translational and rotational geometric drift. A total of 9261 combinations of horizontal translation, vertical translation, and rotation were applied to the generated configuration of 110 reference elements. Translations were investigated over the range from –10 to +10 px, and rotation over the range from –5° to +5°.

Across the entire investigated transformation parameter space, the estimated values agreed with the prescribed values within the numerical precision of the computational procedure. The maximum total translation error was 2.474×10^{-14} px, while the maximum absolute rotation error was 1.665×10^{-14}°. These results confirmed the working hypothesis that the investigated non-periodic spatial configuration with a controlled minimum distance between reference elements contains sufficient geometric information for estimating translational and rotational drift within the defined transformation range.

The conclusion is limited to idealized simulation conditions and known correspondences between reference elements. The results therefore confirm the basic geometric feasibility of the approach rather than provide an assessment of its accuracy and robustness in an actual printing process. Future research should investigate the effects of the reference element detection procedure, unknown correspondences, and other sources of deviation that arise in the practical application of latent reference structures.

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7. References

Alba, A., Vigueras-Gomez, J.F., Arce-Santana, E.R. and Aguilar-Ponce, R.M. (2015) 'Phase correlation with sub-pixel accuracy: A comparative study in 1D and 2D', *Computer Vision and Image Understanding*, 137, pp. 76–87. DOI: 10.1016/j.cviu.2015.03.011

Bridson, R. (2007) 'Fast Poisson Disk Sampling in Arbitrary Dimensions'. In: *ACM SIGGRAPH 2007 Sketches*. Article 22. DOI: 10.1145/1278780.1278807

Bulan, O., Mao, J. and Sharma, G. (2009) 'Geometric distortion signatures for printer identification'. In: *Proceedings of the 2009 IEEE International Conference on Acoustics, Speech and Signal Processing*, 19–24 April 2009, Taipei, Taiwan. DOI: 10.1109/ICASSP.2009.4959855

Chen, L., Feng, C., Ma, Y., Zhao, Y. and Wang, C. (2024) 'A review of rigid point cloud registration based on deep learning', *Frontiers in Neurorobotics*, 17, 1281332. DOI: 10.3389/fnbot.2023.1281332

Chen, Z., Shan, L. and Zhang, T. (2025) 'Hybrid modeling and compensation register control for the speed-up phase of roll-to-roll (R2R) gravure printing presses', *ISA Transactions*, 167, pp. 688–696. DOI: 10.1016/j.isatra.2025.08.046

Cocianu, C.-L., Uscatu, C.R. and Stan, A.D. (2023) 'Evolutionary Image Registration: A Review', *Sensors*, 23, 967. DOI: 10.3390/s23020967

Comino-Trinidad, M., Chica, A. and Andújar, C. (2023) 'Revisiting Poisson-disk subsampling for massive point cloud decimation', *arXiv*, arXiv:2311.17604. DOI: 10.48550/arXiv.2311.17604

de Sousa, S. and Kropatsch, W.G. (2015) 'Graph-based point drift: Graph centrality on the registration of point-sets', *Pattern Recognition*, 48, pp. 368–379. DOI: 10.1016/j.patcog.2014.06.011

Dey, S. (2018) Hands-On Image Processing with Python: *Expert Techniques for Advanced Image Analysis and Effective Interpretation of Image Data*. Birmingham, UK: Packt Publishing, pp. 73–92.

Fu, K., Chen, X. and Wang, M. (2022) 'Global optimization point-set registration based on translation/rotation decoupling for image-guided surgery applications', *Medical Physics*, 49, pp. 7303–7315. DOI: 10.1002/mp.15839

Gafurov, A.N., Park, H., Kim, D., Kim, I., Choi, Y., Oh, D. and Lee, T.-M. (2024) 'Machine direction registration modelling in roll-to-roll screen printing by deep learning'. In: *Proceedings of the 2024 IEEE 18th International Conference on Advanced Motion Control (AMC)*, 28 February–1 March 2024, Kyoto, Japan. DOI: 10.1109/AMC58169.2024.10505681

Jiao, X., Lv, C., Zhao, J., Yi, R., Wen, Y.-H., Pan, Z., Wu, Z. and Liu, Y.-J. (2024) 'Weighted Poisson-disk resampling on large-scale point clouds', *arXiv*, arXiv:2412.09177. DOI: 10.48550/arXiv.2412.09177

Kleijnen, J.P.C. (2008) *Design and Analysis of Simulation Experiments*. 1st ed. New York, NY, USA: Springer, pp. 113–123.

Pei, H., Zhou, W., Zhang, P. and Luo, M. (2023) 'A review of point set registration: From fundamental algorithms to geometric quality inspection of aviation complex parts', *Journal of Advanced Manufacturing Science and Technology*, 3, 2023012. DOI: 10.51393/j.jamst.2023012

Wei, L.-Y. (2008) 'Parallel Poisson disk sampling', *ACM Transactions on Graphics,* 27. DOI: 10.1145/1360612.1360619

Zhang, H., Liu, S., Wang, X., Wei, K. and Chen, L. (2024) 'Research on high precision detection method of register error based on machine vision'. In: Song, H., Xu, M., Yang, L., Zhang, L. and Yan, S. (eds.) *Innovative Technologies for Printing, Packaging and Digital Media.* Singapore: Springer, Volume 1144. DOI: 10.1007/978-981-99-9955-2_10



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