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Comparative Analysis of Direct and Indirect STL Generation Using Structured-Light and Laser Scanning for Digital Preservation of the Sundang Raja Muhamad

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ABSTRACT

The integration of reverse engineering (RE) and 3D scanning technologies has enhanced efforts to digitally preserve cultural heritage artifacts. However, ensuring dimensional accuracy during data processing, particularly in STL file generation, remains a critical challenge. This study investigates the digital reproduction of the Sundang Raja Muhamad, a 500-year-old Melaka weapon of significant historical value, by comparing the dimensional accuracy of two 3D scanning systems (Rexscan CS2+ and T-Track/T-Scan) and two STL workflows (Direct and Indirect). Direct STL files were produced with minimal manipulation, whereas Indirect STL files underwent additional refinement through surface reconstruction and mesh editing. Dimensional fidelity was evaluated using CAD-to-CAD and CAD-to-Part analyses at five key diameter points on the hilt. Results show that Direct STL files consistently preserved higher geometric accuracy, while Indirect STL files exhibited larger deviations due to extended mesh reconstruction, particularly in regions with limited scan accessibility. The most notable error occurred at Point E, where deviation exceeded the study's ±0.30 mm tolerance threshold. In terms of scanning performance, Rexscan CS2 + achieved slightly superior overall dimensional accuracy (85.74%) compared to T-Track/T-Scan (84.84%), especially in areas with fine surface details. However, both systems demonstrated limitations when scanning recessed or obstructed features. The findings highlight the importance of selecting appropriate scanning technology and STL processing methods for heritage preservation. Direct STL workflows and structured-light scanning provide more reliable geometric fidelity, whereas Indirect workflows are better suited for visual enhancement rather than precision applications.

Keywords: Reverse Engineering; Digital Heritage Preservation; 3D Scanning; Dimensional Evaluation, STL File Accuracy

INTRODUCTION

Melaka is a historically significant city in Malaysia that continues to undergo rapid urbanisation driven by population growth and economic development. This transformation has increased the vulnerability of historical artifacts that form the foundation of the city's cultural and political heritage (Feng 2024). Traditional weapons such as the keris, sundang, and other Malay armaments are particularly susceptible to deterioration through environmental exposure, microbial biodeterioration, natural disasters, and theft (Fierascu et al. 2013; Folorunso & Folorunso 2012). Previous studies have shown that factors such as humidity, light intensity, fungal and microbial activity, erosion, and particulate matter can significantly degrade artifacts, resulting in physical deterioration, colour changes, and loss of historical information (Fierascu et al. 2017; Mazzoli et al. 2018; Pedersen et al. 2020).

To address these challenges, digital technologies, particularly reverse engineering (RE), 3D scanning, and computer-aided design (CAD) have become increasingly important in non-destructive cultural heritage documentation (Kantaros et al. 2025; Uğuryol et al. 2025; Yusri et al. 2022). These technologies enable highly precise digital archiving, virtual reconstruction, restoration planning, and the fabrication of physical replicas for conservation and exhibition (Balletti & Ballarin, 2019; Merchán et al. 2019; Peng & Sanchez, 2005; Saalfeld et al. 2021; Segreto et al. 2017; Shakya, 2019; Tausch et al. 2020). However, despite their growing adoption, challenges persist in maintaining dimensional accuracy and surface fidelity during the scanning and mesh-processing stages, especially when dealing with complex geometries or ornate features. Ensuring data integrity during STL file generation and post-processing remains a critical issue in many digital preservation workflows (Sequenzia et al. 2021; Zhang 2014).

Perbadanan Muzium Melaka (PERZIM), the custodian of Melaka's cultural heritage, emphasises preservation and conservation efforts that retain artifacts as closely as possible to their original state (Zuraidi et al. 2011). Among its most significant collections is the Sundang Raja Muhamad, a 500-year-old weapon attributed to Raja Muhamad, later Sultan Mahmud Syah of Melaka (1488-1528). Characterised by its long wavy blade, silver-plated hilt, intricate carvings, and Jawi inscriptions, the sundang is one of Melaka's most iconic heritage artifacts. Its geometric complexity, elaborate detailing, and cultural value make it an ideal subject for evaluating 3D scanning performance in the context of digital heritage preservation.

FIGURE 1. Sundang Raja Muhamad

Although prior studies have addressed the general application of RE and CAD technologies for cultural heritage documentation (Al-Baghdadi, 2017; Cooper, 2019; Xu et al. 2017), limited research specifically examines the differences between Direct and Indirect STL file generation workflows. Direct STL files typically involve minimal post-processing and therefore remain closer to the raw scan geometry. By contrast, indirect STL files undergo further refinement such as smoothing, gap filling, and geometric reconstruction, which may improve surface aesthetics but also introduce dimensional deviations. Previous findings indicate that excessive mesh manipulation can affect geometric fidelity, particularly when scanning artifacts with partially obstructed or intricately carved surfaces (Rojas, 2025; Selden Jr. et al. 2021; Sequenzia et al. 2021; Zhang et al. 2015). This lack of comparative studies highlights a gap in understanding how different STL workflows influence dimensional accuracy for culturally significant objects.

Beyond STL processing, the selection of 3D scanning technology itself plays a crucial role in capturing accurate heritage models. Structured-light and laser-based systems differ in scanning workflow, sensitivity to surface reflectivity, operational constraints, and the ability to capture fine carvings or recessed features. These differences impact scanning efficiency, ease of operation, and suitability for fragile or delicate artifacts. Therefore, in addition to accuracy, the comparison between Rexscan CS2+ and T-Track/T-Scan is essential because each system offers different scanning workflows, line-of-sight capabilities, operator dependency levels, and performance in capturing complex or obstructed regions. These factors directly influence the practicality of using each system within museum-based heritage preservation environments.

For these reasons, this study aims to compare the dimensional accuracy of Direct and Indirect STL files generated using two different non-contact 3D scanning systems, they are: (i) Rexscan CS2+ and (ii) T-Track/T-Scan, through the case study of the Sundang Raja Muhamad. By addressing gaps in prior work and analysing the effects of different scanning and processing workflows, this research provides insights into optimising RE methods for digital archiving, replication, and long-term preservation of culturally significant artifacts.

METHODOLOGY

ARTIFACT SELECTION

The Sundang Raja Muhamad was selected as the subject of this study due to its cultural significance and the preservation priority identified by PERZIM. As one of the few surviving weapons attributed to Raja Muhamad, the sundang represents an important component of Melaka's historical identity. The artifact measures 68.2 cm in overall length and features a wavy blade, silver-plated hilt, intricate carvings, and Jawi inscriptions. These geometric complexities and ornate details make the sundang an appropriate test object for evaluating the capability of different 3D scanning technologies to capture fine surface features accurately.

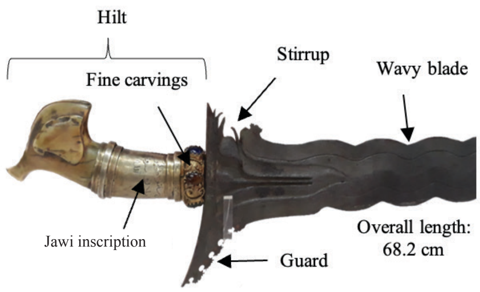

FIGURE 2. Features of the sundang

3D SCANNING PROCESS AND STL FILE GENERATION

The reverse engineering (RE) workflow consisted of six phases: (i) artifact selection, (ii) scanning and data acquisition, (iii) point cloud generation, (iv) mesh manipulation, (v) Direct and Indirect STL file generation, and (vi) dimensional evaluation. Two non-contact 3D scanning systems were used: (i) Rexscan CS2+ (structured light scanner) and (ii) T-Track/T-Scan (laser scanner). Both systems were used to acquire multiple scan views of the sundang. The raw scan data were aligned and merged to form a watertight digital model of the artifact.

Two STL file types were then generated for each scanner. Firstly, Direct STL Generation, where Direct STL files were produced using minimal processing. Raw scan views were aligned and merged, and basic mesh repair procedures were applied, including removal of isolated noise points, filling of small gaps, and global light smoothing. No surface reconstruction, curve fitting, or advanced polygon modifications were performed. The same Direct STL workflow was consistently applied to both scanning systems to ensure methodological uniformity. Secondly Indirect STL Generation, where Indirect STL files were generated by refining the Direct STL models through extended processing in CATIA software. Additional mesh operations included curvature-based surface reconstruction, selective mesh decimation to reduce irregularities, smoothing of rough areas, and contour refinement to enhance visual appearance. These operations are known to improve surface continuity but may also introduce geometric deviations, especially in regions where the original scan data were incomplete.

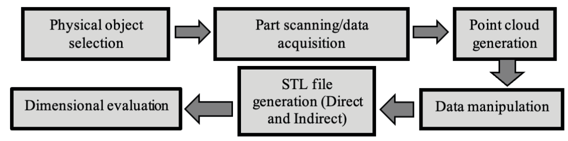

FIGURE 3. Phases of the 3D scanning process

DIMENSIONAL INSPECTION AND MEASUREMENT POINTS

To evaluate dimensional fidelity, five diameter points (A-E) were selected along the hilt of the sundang (refer Figure 4). These points represent cylindrical regions of varying curvature and accessibility. The selection was limited to non-carved and non-fragile sections of the artifact to comply with PERZIM's conservation requirements. Each diameter was measured using a digital Vernier caliper (refer Table 2). To ensure reliability, each measurement was repeated three times, and the average value was recorded. Although the sundang contains additional decorative and geometric features, these could not be physically measured without risking damage to delicate or carved regions. Therefore, the selected diameter points offer a safe, representative basis for dimensional comparison while respecting artifact preservation guidelines.

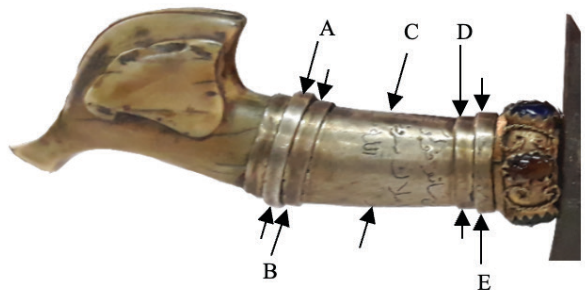

FIGURE 4. Measured diameter points

TABLE 2. Average diameter measurement

Measured diameter points	Average diameter (mm)
A	29.72
B	26.85
C	24.72
D	26.65
E	29.34

DIMENSIONAL EVALUATION: CAD-TO-CAD AND CAD-TO-PART ANALYSIS

Two evaluation methods were used to assess dimensional accuracy. Firstly, CAD-to-CAD Analysis. This analysis compared the Indirect STL file to the Direct STL file for each scanning system. The Direct STL served as the reference model because it retained the closest representation of the raw scan data. Deviation colour maps were generated to visualise geometric differences across the models. These maps highlighted areas where surface reconstruction, smoothing, or mesh modification during Indirect STL generation introduced dimensional changes. Secondly, CAD-to-Part Analysis. This analysis compared the Direct and Indirect STL files to the physical artifact. The averaged caliper measurements for each diameter point (A-E) were compared with the corresponding dimensions extracted from the STL models. Accuracy percentages were calculated to quantify the fidelity of each scanning workflow and identify regions where data insufficiency or mesh reconstruction caused deviation.

The combined use of structured-light and laser scanning systems, coupled with two STL generation workflows (Direct and Indirect), enabled a comprehensive assessment of how different RE processes affect dimensional accuracy. These evaluations provide insights relevant to digital heritage preservation, especially when balancing surface quality with geometric fidelity during the digitisation of culturally significant artifacts.

RESULTS AND DISCUSSION

CAD-TO-CAD ANALYSIS

The CAD-to-CAD analysis compared the Direct and Indirect STL files generated from the Rexscan CS2+ scanner to evaluate dimensional deviations introduced through extended mesh manipulation. The Direct STL file served as the reference model because it underwent minimal processing and therefore represented the closest approximation to the raw scan data. Deviation maps were generated to visualise dimensional differences between the two STL files. Figure 5 shows the deviation color map of the CAD data and the overall deviation values at each diameter point (A-E) are presented in Table 3.

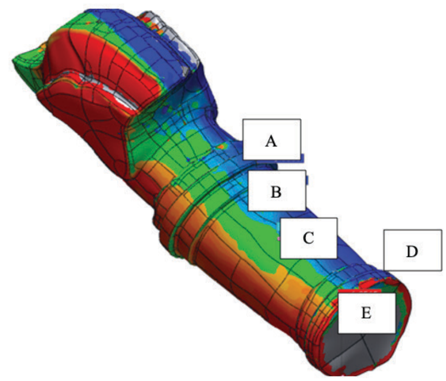

FIGURE 5. Deviation color map of the CAD data

TABLE 3. Average diameter measurement

Point	Deviations	Color indicator
A	-1.0035	Blue
B	-0.8263	Blue
C	-0.1877	Green
D	-5.9933	Blue
E	+6.9565	Red

Point E recorded the highest deviation at +6.9565 mm, indicating substantial geometric distortion in the Indirect STL file. This region lies near intricate carvings and the guard, where scanning accessibility was limited. In the absence of sufficient point cloud data, the reconstruction functions applied during Indirect STL generation filled missing information using surface approximation, leading to measurable enlargement.

Based on established practices in mesh-based dimensional inspection of heritage objects, a tolerance threshold of ±0.30 mm was adopted for this study. Deviations exceeding this threshold indicate loss of geometric fidelity. Under this criterion, deviations at points A, B, D, and E fall outside acceptable tolerance, with point D showing significant undersizing at -5.9933 mm. These areas correspond to recessed or occluded regions where the scanner had limited line-of-sight, increasing reliance on algorithmic reconstruction during post-processing.

Point C exhibited the smallest deviation at -0.1877 mm, which remaining within tolerance. This was likely due to clearer line-of-sight and better surface visibility during scanning. Overall, the deviation map revealed a mixture of submerged (blue), acceptable (green), and emerged (red) regions across the hilt, with the middle section displaying inconsistent reconstruction outcomes. These findings confirm that while Indirect STL processing enhances surface continuity, it can compromise geometric accuracy when scan data are incomplete.

CAD-TO-PART ANALYSIS

The CAD-to-Part analysis evaluated the dimensional accuracy of the STL models against actual measurements of the Sundang Raja Muhamad artifact. The averaged caliper measurements for points A-E were compared with corresponding dimensions extracted from Rexscan CS2+ and T-Track/T-Scan models. Results are summarised in Table 4.

Overall, both scanners demonstrate relatively high dimensional accuracy when compared to the original artifact. Rexscan CS2+ shows slightly superior accuracy, with an average of 85.74%, compared to 84.84% for T-Track/T-Scan. At points A and C, Rexscan produced notably closer measurements to the actual dimensions, while T-Track/T-Scan showed better performance at points E and F. Notably, point D showed the lowest accuracy from both scanners, particularly Rexscan (64.73%), which may indicate occlusion or scanner instability in capturing recessed or shaded surfaces. These findings confirm that Rexscan CS2+ consistently delivers higher accuracy in capturing intricate geometries, making it more suitable for applications involving cultural heritage preservation. However, T-Track/T-Scan still demonstrates adequate performance in less obstructed or simpler surface regions.

TABLE 4. Comparison of average dimension readings

	Actual Sundang Raja Muhamad	CAD data from Rexscan CS2+		CAD data from T-Track/T-Scan	
Measured diameter points	Average diameter (mm)	Average diameter reading (mm)	Accuracy (%)	Average diameter reading (mm)	Accuracy (%)
A	29.72	29.23	98.35	21.57	72.58
B	26.85	28.89	107.60	27.30	101.68
C	24.72	23.96	96.92	23.40	94.66
D	26.65	17.25	64.73	20.35	76.36
E	29.34	21.63	73.72	23.29	79.38
F	31.52	23.04	73.10	26.59	84.36
Average dimensional accuracy (%)			85.74		84.84

The comparative analysis reveals that the Direct STL file retains higher dimensional accuracy due to its minimal manipulation pipeline. While the Indirect STL may offer improved surface smoothness, the trade-off is evident in its dimensional reliability, particularly in areas that require reconstruction. From a conservation and digital manufacturing perspective, these results highlight the importance of choosing appropriate scanning and processing workflows based on preservation goals, whether to prioritise geometric fidelity, visual aesthetics, or both. Moreover, these insights are crucial when fabricating physical replicas using additive manufacturing techniques such as laser sintering (LS), where dimensional errors could compound in downstream applications.

Overall, both scanners demonstrated good performance in capturing major dimensions of the sundang. Rexscan CS2+ achieved slightly higher average accuracy (85.74%) compared to T-Track/T-Scan (84.84%). Rexscan showed strong performance at points A and C, corresponding to areas with more uniform geometry and clearer visibility. T-Track/T-Scan performed relatively better at points E and F, where laser-based scanning may have been more effective in penetrating areas with surface reflectivity.

Point D recorded the lowest accuracy for both systems, highlighting a region where complex carvings and recessed features created scanning difficulties. These occlusions produced insufficient point cloud density, leading to inaccuracies during surface fitting and STL generation.

The results indicate that structured-light scanning (Rexscan CS2+) is particularly effective for detailed, non-reflective surfaces, whereas laser scanning (T-Track/T-Scan) remains suitable for simpler or less obstructed regions. However, both systems exhibit limitations when scanning deeply carved or shaded areas of heritage artifacts.

The comparative analysis demonstrates clear differences between Direct and Indirect STL workflows. Direct STL files retained higher geometric fidelity due to minimal manipulation, whereas Indirect STL files displayed greater dimensional deviation, especially in regions with limited scan coverage. Although Indirect STL models produced visually smoother surfaces, the trade-off was measurable geometric distortion, which unsuitable for applications requiring dimensional precision such as physical replica fabrication or analytical restoration.

Similarly, the scanning systems exhibited complementary strengths. Rexscan CS2+ produced generally higher accuracy for most regions, likely due to its structured-light capability to capture fine surface details. T-Track/T-Scan provided adequate accuracy but encountered greater difficulty with reflective and obstructed surfaces. These findings highlight the importance of selecting an appropriate scanning system and processing workflow based on the specific geometry and preservation requirements of heritage artifacts.

CONCLUSION

This study evaluated the dimensional accuracy of Direct and Indirect STL files generated using two non-contact 3D scanning systems, which are Rexscan CS2+ and T-Track/T-Scan in the digital preservation of the Sundang Raja Muhamad: a culturally significant 500-year-old Melaka heritage artifact. The findings highlight clear differences in geometric fidelity between STL workflows and scanning systems.

Direct STL files that underwent minimal mesh manipulation consistently preserved higher dimensional accuracy compared to Indirect STL files. Extended post-processing in the Indirect workflow including smoothing, surface reconstruction, and gap filling improved visual surface continuity but introduced dimensional deviations, particularly in regions with limited scan accessibility. This was most evident at measurement point E, where deviation surpassed the acceptable tolerance threshold. These results emphasise that excessive mesh refinement can compromise geometric authenticity, an important consideration in heritage digitisation where fidelity to the original artifact is crucial.

In the comparison of scanning technologies, Rexscan CS2+ demonstrated slightly superior overall accuracy (85.74%) over T-Track/T-Scan (84.84%). The structured-light system showed better performance in capturing fine carvings and non-reflective surfaces, whereas the laser-based system performed adequately in less complex regions but struggled with deeply recessed or obstructed features. Both systems exhibited limitations in areas affected by line-of-sight constraints and surface occlusions.

Overall, the study provides meaningful insights for digital heritage preservation workflows. When dimensional accuracy is the primary requirement, such as for documentation, geometric analysis, or fabrication of replicas, Direct STL generation and structured-light scanning offer the most reliable results. Indirect STL workflows may still be useful for aesthetic visualisation or virtual exhibitions but should be applied with caution for precision-dependent applications. Future work should explore hybrid scanning strategies, adaptive mesh processing, and automation-assisted reconstruction techniques to balance surface quality with dimensional stability, especially for complex heritage artifacts with intricate geometries.

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DECLARATION OF COMPETING INTEREST

None.

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