A COMPARISON OF STRUCTURED LIGHT SCANNING AND PHOTOGRAMMETRY FOR THE DIGITISATION OF PHYSICAL PROTOTYPES

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ABSTRACT

Physical prototyping during early stage design typically represents an iterative process. Commonly, a single prototype will be used throughout the process, with its form being modified as the design evolves. If the form of the prototype is not captured as each iteration occurs understanding how specific design changes impact upon the satisfaction of requirements is challenging, particularly retrospectively.

In this paper two different systems for digitising physical artefacts, structured light scanning (SLS) and photogrammetry (PG), are investigated as means for capturing iterations of physical prototypes. First, a series of test artefacts are presented and procedures for operating each system are developed. Next, artefacts are digitised using both SLS and PG and resulting models are compared against a master model of each artefact. Results indicate that both systems are able to reconstruct the majority of each artefact's geometry within 0.1mm of the master, however, overall SLS demonstrated superior performance, both in terms of completion time and model quality. Additionally, the quality of PG models was far more influenced by the effort and expertise of the user compared to SLS.

Keywords: Design process, New product development, Prototyping, Conceptual design

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1 INTRODUCTION

A prototype can be defined as a physical instantiation of a product, which is created to help resolve one or more issues during the development of the product (Otto and Wood, 2001). The specific purpose of prototyping a product varies across applications, however, it is broadly considered as either a divergent tool used to aid the exploration of a design space or a convergent tool used to evaluate a design against its requirements and specification (Jensen et al., 2016). Regardless of the purpose, it is common for designers to produce multiple iterations of a prototype, sequentially testing and refining until a satisfactory design is reached (Christie et al., 2012), with empirical evidence suggesting that increasing the number of iterations performed can significantly improve the performance of a design team (Dow et al., 2009). Furthermore, it has been suggested that the rate at which iteration occurs can directly affect the success of the design process, with faster iteration helping to reduce, for example, design fixation (Camburn et al., 2017).

Prototypes are by their nature a 'one off' artefact, therefore, when iteratively prototyping a design it is common for designers to physical modify the same prototype as the design evolves, a process referred to as Evolutionary Prototyping (Reed Doke, 1990). This can have negative consequences for the design process; first, disseminating prototype designs can be challenging, with possession of the prototype a zero-sum game. Second, as previous iterations of the prototype cannot be examined once superseded, tracking how the various iterations have met or impacted upon the satisfaction of requirements and design goals is also challenging, particularly retrospectively. This is problematic if the design ultimately converges to a suboptimal solution, with it not necessarily possible to revert back to previous iterations. To mitigate for this designers must ensure each iteration is comprehensively documented, essentially conducting a manual revision control process, which impacts upon the cost, quality and time associated with the design process (Jones et al., 2019). As such, attempts have been made to aid the process of revision control during a prototyping process through the development of tools for capturing digital representations of each iteration of a prototype. Work in this area has, to date, focussed on capturing 2D images of prototypes to produce a 'snapshot' of each iteration (Barhoush et al., 2019; Erichsen et al., 2020). Whilst 2D representations can certainly provide an indication of a physical artefact's design, their efficacy in communicating the intricacies of each iteration is limited by their inability to capture and convey the detailed geometry of a physical artefact. It has been suggested by Hannah et al. (2012) that higher fidelity representations of designs can lead to more accurate interpretation by third parties, therefore, it can be hypothesised that through interrogation of a 3D representation of a physical prototype a more comprehensive and intuitive understanding of its design can be obtained. Furthermore, by capturing 3D geometry it becomes possible to feasibly compute the physical change in a prototype between iterations, again in a manner analogous to software version control.

The process of generating a 3D virtual representation of a physical prototype is referred to as digitisation. Historically, digitising a physical artefact involved a manual process of measurement and reconstruction typically conducted by an expert in metrology and/or draughting, representing significant effort and expertise. However, automated technologies for the digitisation of physical artefacts are increasingly available, with a wide range of contact and non-contact solutions developed for this purpose, representing different techniques, levels of performance and price points (Savio et al., 2007).

Given the potential affordance of digitisation of physical prototypes this paper seeks to assess the performance of two different digitisation techniques: structured light scanning (SLS) and photogrammetry (PG), when tasked with capturing the geometry of a series of test artefacts. For successful integration within a prototyping process, digitisation must be possible without requiring significant effort or highly specialised expertise; adding inertia into a typically creative process is likely to impact negatively and thus a designer should be able to perform digitisation in a simple and timely manner. Accordingly, the two digitisation systems are evaluated not only in terms of their ability to accurately and completely reconstruct an artefact's geometry but also in terms of their useability. This work is thus intended to provide the reader with an indication of the capabilities, relative merits and challenges associated with each technique based upon the state of extant technology, rather than purely to characterise the technical capabilities of the specific digitisation systems investigated. The paper first presents the experimental method employed, including the design of test artefacts and development of digitisation procedures. Next, the results of digitisation via SLS and PG are presented and evaluated via a series of qualitative measures. Finally, the performance of

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each system is compared in both quantitative and qualitative respects and ultimately the suitability of each for utilisation within the prototyping process is considered.

2 EXPERIMENTAL METHOD

Two different COTS digitisation systems were used during the study, one based upon structured light scanning (SLS) and one photogrammetry (PG). Experimental work sought to understand how such systems are used, what they are capable of producing and to identify any limitations or challenges with respect to digitisation of prototypes in the context of the design process. The experimental method broadly consisted of using each system to digitise an identical set of artefacts to produce a watertight mesh representation of each artefact and subsequently evaluating the quality of each model. As described in Section 1, within the context of digitising physical prototypes during a product development process, in addition to their technical capabilities the usability of each systems is an important consideration, thus evaluation must consider both quantitative and qualitative aspects:

- Quantitative: relating to the ability of each system to accurately and completely reconstruct the external geometry of each artefact.
- Qualitative: relating to the effort and expertise required upon the part of the user to digitise each artefact.

2.1 Test Artefacts

To explore the capabilities of each system a series of physical artefacts to be digitised were required. For this purpose four bespoke artefacts (referred to as Blocks, Cylinders, Triangular Prisms and Lion, (Figure 1) were designed, based upon the principles of artefacts used for similar purposes within literature, such as the NIST Additive Manufacturing Test Artefact (Moylan et al., 2014).

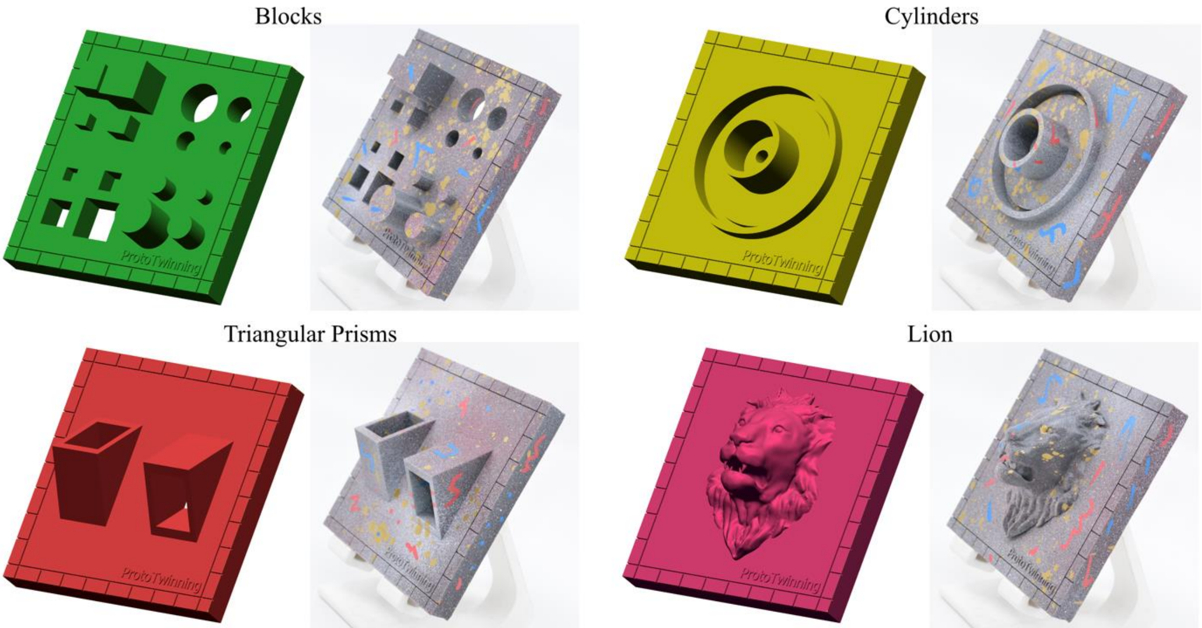

Figure 1: Test artefacts in virtual and physical form.

Artefacts were designed such that they each contain a unique set of geometric features including primitive and/or freeform shapes, which were arranged such that they would promote occultation, a common challenge for digitisation systems. Designs aimed to encompass a non-exhaustive but comprehensive range of geometric features which can also be produced using common prototyping techniques such as clay modelling and 3D printing, in doing so highlighting any features/ characteristics which may be challenging to digitise in practice.
Artefacts were manufactured from PLA using an Ultimaker 3 3D printer. Due to the inaccuracies inherent to any manufacturing process, the as-built geometry of each physical artefact will deviate from its as-designed geometry. To account for this, each artefact was first digitised using an RX

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Solutions DeskTom CT scanning system capable of ~0.012mm accuracy, to produce a master model of each against which SLS and PG models could be evaluated.
To quantify the accuracy of each SLS and PG model in comparison to its master, eight measures were defined:

1. Production time: the total time to produce each model, including data capture and processing.
2. Mean error: the mean (RMS) deviation between equivalent points on each model.
3. Error variance: the variance of the distribution of errors between equivalent points.
4. Percentage within tolerance: the percentage of deviations within a specified tolerance.
5. Maximum error: the maximum error measured between any two equivalent points.
6. Width error: the difference in the width of the subject and master models.
7. Height error: the difference in the height of the subject and master models.
8. Depth error: the difference in the depth of the subject and master models.

2.2 Experimental Procedures

Prior to the completion of the formal study a period of investigation was undertaken to gain familiarity with each system and ultimately to devise a suitable operational procedure for digitising artefacts using each system. Subsequently, each artefact was digitised using each system's respective method to produce a mesh representation. Three scans of each artefact were performed to assess the consistency of each system, however, no significant variance was identified across repeat scans, so only one scan per artefact is reported here.

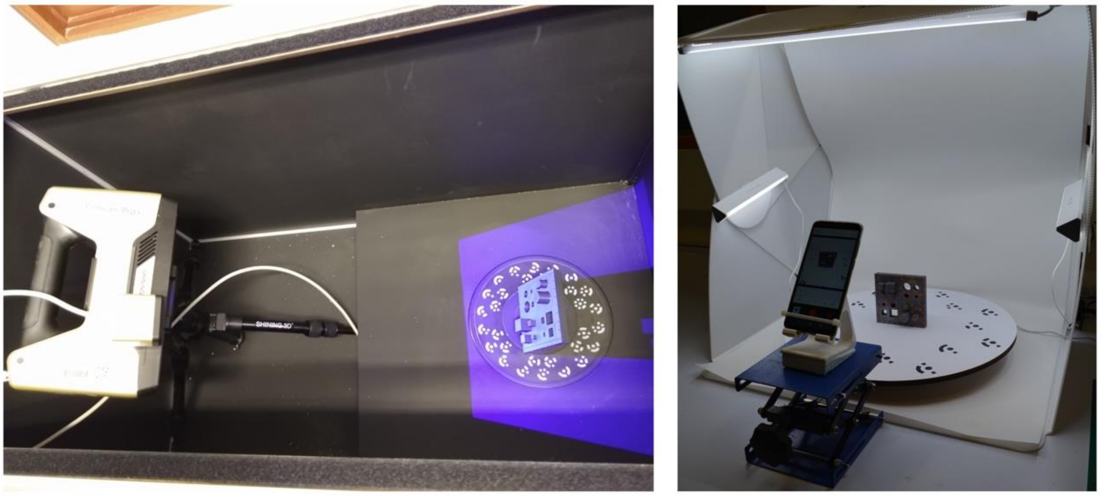

Figure 2: Hardware setups used within SLS (L) and PG (R) digitisation procedures.

2.2.1 Structured Light Scanning

The principle of structured light scanning (SLS) involves projecting a pattern (typically stripes) of visible light onto the surface of an artefact. When the light hits the artefact's surface it will be distorted by the specific geometry present, which is captured by a camera. Captured images are then analysed and, based upon the nature of the distortion which has occurred, the geometry of the artefact can be estimated and thus a 3D model reconstructed.
An Einscan Pro+ (Shining 3D, n.d.) SLS scanner and turntable capable of a stated accuracy of 0.05mm was used within the study. The scanner was static throughout tests and the turntable used to automatically rotate artefacts between individual scans to expose additional surfaces (shown in Figure 2 (L)). The turntable incorporates coded targets to enable the system to track the location and orientation of an artefact across individual scans as well as to estimate the absolute size of the artefact.
As SLS utilises visible light its performance is significantly affected by ambient lighting conditions and necessitates high contrast between an artefact and its surroundings. Thus, the system was installed within a lightproof enclosure and all interior surfaces of the enclosure were blackened. The surface properties of an artefact can also affect SLS performance, with highly reflective or transparent surfaces particularly challenging, however, no such issues were encountered during testing.

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After a period of testing, a procedure for SLS scanning of artefacts was devised:

1. Artefacts were centred on the turntable and supported in position if necessary.
2. Each was scanned using 12 scans – there is a trade-off between the number of scans and the accuracy of the model created – more scans means more data points so better coverage of geometry, however, when the data from multiple scans of the same geometric feature are combined a filtering effect is often produced due to slight variance in the scan data, reducing absolute accuracy.
3. Reorientated to enable areas of surface occluded during first set of scans to be scanned.
4. Scanned again using 12 scans.
5. Two sets of scans combined using software.
6. If any obvious regions of the artefact's surface are still not captured then the artefact is reorientated and an additional targeted scan performed.
7. Any data points associated with materials used to support an artefact were manually removed.
8. Finally, scanned data is meshed using watertight, high fidelity settings within the Einscan software to produce an STL.

2.2.2 Photogrammetry

Photogrammetry (PG) refers to the process of estimating the surface geometry of an artefact from analysis of 2D images of the artefact. Typically, the greater the number of photos of an artefact provided the better its geometry is able to be reconstructed, however at the cost of increased computation. The specific techniques and algorithms employed for this task vary but the overall process typically involves firstly analysing each image to identify common features, next analysing how those features change between images to estimate relative camera positions and finally using this knowledge to estimate the relative position of each feature through triangulation. From the perspective of the user, this represents an essentially 'black box' process. Within this study artefacts were photographed using a Motorola G7 (Motorola, n.d.) smartphone and images processed using the commercially available Agisoft Metashape (Agisoft, n.d.) software to reconstruct geometry (shown in Figure 2 (R)).

The PG procedure comprised of three major steps:

1. Capture photographs.
   - Artefacts were placed on an electronic turntable to permit controlled rotation and within a light box to provide controlled diffuse light.
   - Coded targets were placed upon the turntable at known locations to assist the software in aligning between photos and scaling the output model.
   - Each artefact photographed in two orientations to enable capture of the entire external surface.
   - Per orientation 3 rings of 24 photos were taken, at elevations of ~ 0°, 20° and 40°.
   - Photos were 3072x3072px resolution and taken from ~300mm with ~400mm FOV, thus theoretically permitting capture of features >=~0.13mm.
2. Process photographs within Metashape.
   - Photos loaded into Metashape in 2 'chunks', with each containing one orientation's photos.
   - Next, computational processes completed (marker detection, photo alignment, depth estimation and dense point cloud production).
   - Once point clouds are generated any necessary manual cleaning is performed (e.g. removal of spurious data).
   - Finally, alignment between chunks is computed and highest-possible density mesh built.
3. Export mesh data as STL.

During testing the success of the PG process was highly dependent upon the surface characteristics of the subject artefact, corroborating similar reports within literature (Sims-Waterhouse et al., 2017). Artefacts which presented significant variability in texture across their surface, such as organic materials (e.g. wood), were much more successfully reconstructed than isotropic materials such as aluminium, where there are few unique features to aid triangulation. To mitigate for this limitation a speckling effect (patternation) was applied to the surface of artefacts prior to scanning to increase surface variability. Various means for generating speckling were investigated, with the best results obtained through a combination of applying random patterns using coloured spray paints and pens

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(Figure 3). When applied to plastic parts this process is considered essentially irreversible as removal necessitates the use of solvents liable to dissolve plastics.

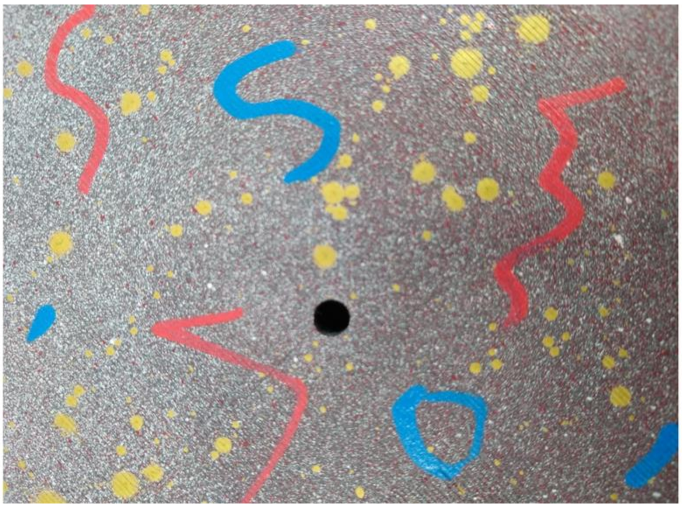

Figure 3: An example of the surface patternation applied to each test artefact prior to digitisation via photogrammetry.

3 RESULTS AND FINDINGS

Across tests the time taken to complete each process (including both scanning and processing activities) was consistently ~20 mins and ~45 mins per artefact for SLS and PG respectively. Once obtained, models were analysed using Geomagic Design X to determine both the overall deviation between equivalent models, as well as to measure specific dimensions of interest. Measurements of the major dimensions of each model were obtained by placing a bounding box around each model. To permit analysis of overall deviation the equivalent models of each artefact were aligned digitally to the master model using a two-step coarse and fine approach. An initial coarse alignment was achieved by manually selecting three points common across models. Next, the alignment was refined automatically using a best fit algorithm, in which the geometry of each model is first analysed to identify common points after which a least-squares method is used to reorientate one model until the sum of squares between the common points is minimised (3D Systems, 2020). Once all models were aligned the deviation between the surface geometry of the master and each SLS and PG model was computed, that is, the Euclidean distance between its computed equivalent point. A colour map was then produced for each pair of models, in which any deviation between surfaces <0.1mm is coloured green, any deviation between 0.1mm and 2mm is increasingly red or blue (depending on sign) and any deviation >2mm is grey (Figure 4). A 0.1mm tolerance was selected to reflect the approximate dimensional accuracy of a plastic artefact when printed on a typical FDM-based 3D printer (Loflin et al., 2019; Melenka et al., 2015).

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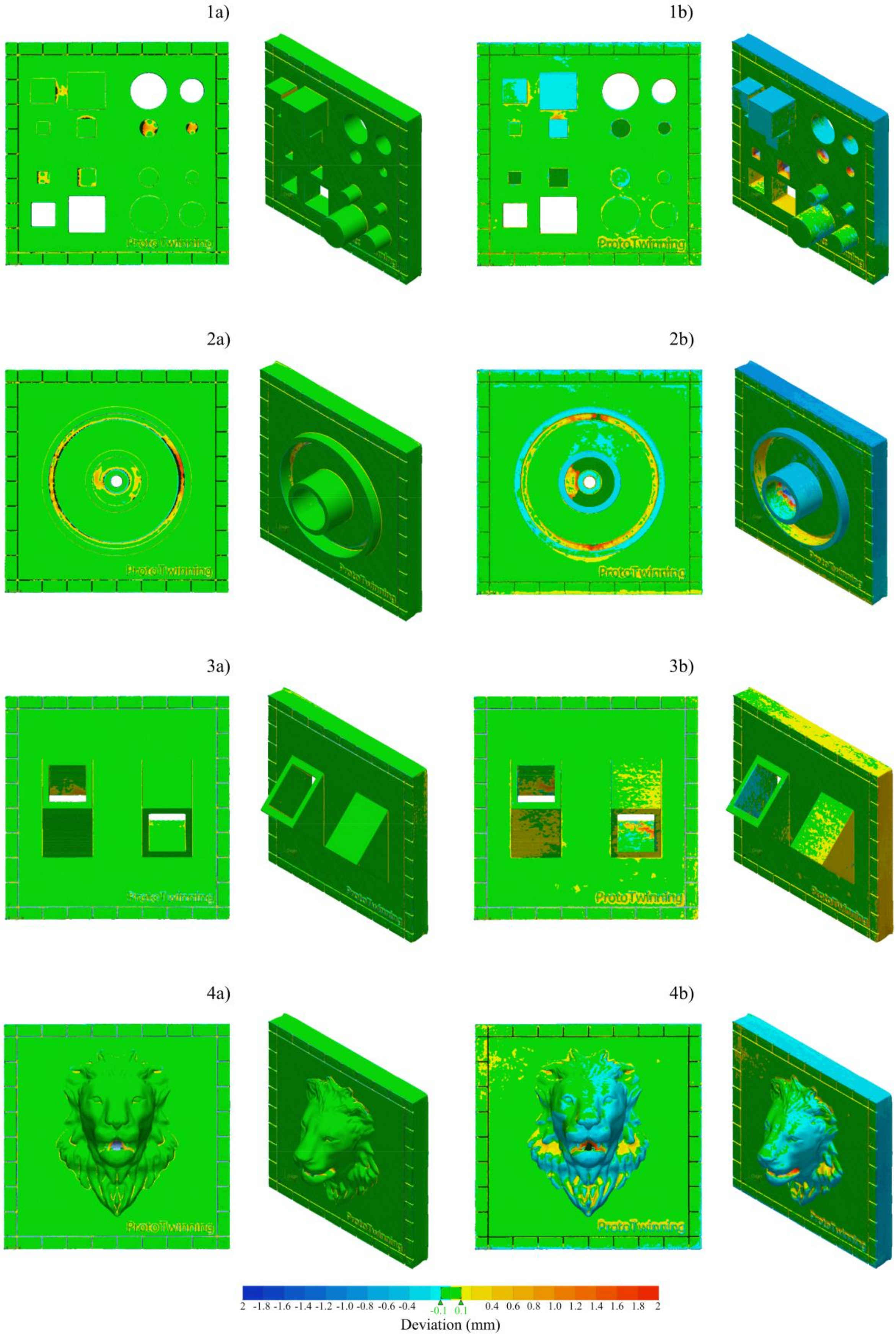

Figure 4: Calculated deviation between master and SLS (a) and PG (b) models for each artefact (Blocks (1), Cylinders (2), Triangular Prisms (3) and Lion (4)). Green indicates equivalent points are within a tolerance of 0.1mm.

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Overall, the mean error associated with SLS models was ~0.05mm compared to ~0.3-0.4mm for PG, resulting in >95% of SLS points being within the 0.1mm tolerance, compared to only ~50% for PG models (Table 1). In addition, the variance of PG models was an order of magnitude greater than SLS models, indicating that errors were distributed more widely across each model, as indicated by the greater errors in overall scale associated with PG models. Having said that, the magnitude of maximum error of both SLS and PG models (4-8mm and 13-16mm respectively) indicates that there were specific locations within each artefact which both systems struggled to reconstruct accurately. Through inspection of Figure 4 these can be identified as grey coloured areas and typically represent areas of significant or complete occlusion, such as the gutter within Cylinders and the Lion's mouth.

*Table 1: Summary of measures calculated across models. Values marked $^+$ represent which digitisation method performs better. Row marked * indicates values used to calculate overall accuracy.*

		Artefact							
		Blocks		Cylinders		Triangular Prisms		Lion	
Method		SLS	PG	SLS	PG	SLS	PG	SLS	PG
Alignment Error (RMS) (mm)		0.0272$^+$	0.1396	0.0336$^+$	0.2833	0.0440$^+$	0.2081	0.0386$^+$	0.2620
Mean Error (RMS) (mm)*		0.0403$^+$	0.2812	0.0479$^+$	0.3842	0.0499$^+$	0.2861	0.0464$^+$	0.2924
Error Var. (mm)		0.0012$^+$	0.0790	0.0017$^+$	0.1460	0.0017$^+$	0.0746	0.0010$^+$	0.0625
Within Tol. (%)		97.99$^+$	52.60	97.76$^+$	41.87	96.37$^+$	43.38	98.43	44.54$^+$
Max Absolute Error (mm)		5.790$^+$	13.243	8.131$^+$	15.860	3.844$^+$	14.433	5.474$^+$	16.503
Width (mm)	Master	100.358		100.262		100.252		100.279	
	Error	0.213	0.034$^+$	0.485	0.173$^+$	0.101$^+$	1.403	0.234$^+$	0.677
Height (mm)	Master	100.202		100.082		99.960		100.117	
	Error	0.142$^+$	0.681	0.778	0.231$^+$	0.050$^+$	0.784	0.113$^+$	1.208
Depth (mm)	Master	27.963		27.94		33.344		41.197	
	Error	0.113	0.024$^+$	0.245	0.116$^+$	0.040$^+$	0.245	0.086$^+$	0.407

4 DISCUSSION

4.1 Quantitative Performance

Typically, the SLS system reproduced each model to a higher level of dimensional accuracy compared to the PG system, realising a mean error of ~0.045mm across models compared to ~0.3mm for PG. However, overall, an inspection of models indicates that both systems were able to reconstruct a clear visual representation of each artefact's macro geometry. The scale of most features within each artefact is significantly greater than the accuracy demonstrated by each system and thus most features are well reconstructed. Considering the typical scale of geometric features likely to be present within a prototype of a consumer good such as a mobile phone or computer mouse certainly based upon their demonstrated performance both systems can be expected to capture and reconstruct salient features. However, at specific locations within certain artefacts both systems did incur significant errors, with some features missing entirely within models. Primarily, this was a consequence of occlusion and/or shadows within captured images; unlike a CT system both SLS and PG systems rely upon being able to 'see' features in order to reconstruct them, thus, if a feature is occluded by another feature or is not well lit then neither will be able to reconstruct it. To mitigate for this further, targeted capture and/or improved lighting could enhance the quality of models, at the cost of increased capture and processing time. For example, each system's imaging device remained static throughout capture; by manipulating the imaging device itself further orientations and closeups of challenging areas could be captured.

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4.2 Qualitative Assessment

Between systems the total time to produce models was almost double for PG, primarily representing the additional computational time. In general, the time taken by each system will be dictated by the quantity of data captured, that is, the number of individual images taken (capture time) and the resolution of those images (processing time). This results in each system presenting a trade-off between model accuracy and completeness, and production time; the more data that is captured typically the better each system will be able to reconstruct an artefact but the longer it will take to produce.

Production time was also impacted by the quantity of manual data cleaning required. SLS models typically only required cleaning in instances where additional objects had been used to physically support artefacts during scanning (e.g. Lego bricks and plasticine). In contrast, PG models often required significant manual cleaning of spurious data points, particularly around the edges of artefacts and at the turntable-artefact interface.

In this respect, SLS also had the advantage of being able to scan artefacts without requiring any surface treatment. To enable PG to comprehensively identify each artefact's geometry it was necessary to apply patternation; this not only consumed time but irreversibly changed each artefact. It should be noted however that reversible techniques have been proposed for this purpose, such as laser specking, in which a light pattern is projected onto the surface of an artefact (Sims-Waterhouse et al., 2017). Furthermore, if artefacts naturally present more varied surface patterns (e.g. organic materials) then the performance of PG will typically be significantly improved compared to when applied to less variable surface patterns, such as raw 3D printed parts, clay models or cardboard structures, for example.

The performance of both systems was influenced by the user, in particular with respect to the orientation and order of scans conducted. To produce a single model which represents the entirety of an artefact's external geometry typically necessitates scanning it in multiple physical orientations and subsequently aligning these digitally. If there is sufficient overlap in the features present in each scan then typically both systems were able to automatically align scans without error. However, if the user scans an artefact with little overlap between scans manual alignment is required, increasing the effort and expertise required of the user.

5 CONCLUSION

Two techniques for producing 3D digital representations of physical artefacts, structured light scanning (SLS) and photogrammetry (PG) were investigated to assess their capabilities, limitations and useability within the context of physical prototyping. Overall, both systems demonstrated an ability to reconstruct the major features of each artefact to a 0.1mm tolerance, sufficient to reconstruct the macro geometry of each artefact. The accuracy demonstrated by each system was consistent across the dimensions of each model and repeatable across multiple scans, however, specific geometric features proved challenging for either system to reproduce, primarily as a consequence of occlusion. Accordingly, value could be found in the production of an application guide to support users, highlighting common pitfalls and suggesting improvements to maximise the quality and thus value of models produced.

Between the two systems SLS demonstrated a clear advantage in not requiring pre-treatment of artefacts; the PG method could feasibly be modified to mitigate for this limitation by employing a reversible surface treatment. Considering the context of digitising physical prototypes within a product development process the time required to produce models using either system is likely acceptable at sub one hour. However, a level of user expertise is certainly required to extract fully-featured and clean models, particularly in the case of PG, where the quality of models produced was significantly affected by the interventions of the user. Overall, based upon the technological maturity observed neither technique is able to be considered 'plug and play', however, both represent feasible solutions for the digitisation of physical prototypes.

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REFERENCES

3D Systems, 2020. How does Best Fit Alignment determine how the parts are aligned? [WWW Document]. URL https://support.3dsystems.com/s/article/How-does-Best-Fit-Alignment-determine-how-the-parts-are-aligned?language=en_US (accessed 11.15.20).

Agisoft, n.d. Metashape Professional Edition [WWW Document]. URL https://www.agisoft.com/features/professional-edition/ (accessed 11.16.20).

Barhoush, Y.A.M., Erichsen, J.F., Sjöman, H., Georgiev, G.V., Steinert, M., 2019. Capturing Prototype Progress in Digital Fabrication Education, in: Proceedings of the Design Society: International Conference on Engineering Design. pp. 469–478. https://doi.org/10.1017/dsi.2019.50

Camburn, B., Viswanathan, V., Linsey, J., Anderson, D., Jensen, D., Crawford, R., Otto, K., Wood, K., 2017. Design prototyping methods: state of the art in strategies, techniques, and guidelines. Design Science 3. https://doi.org/10.1017/dsj.2017.10

Christie, E.J., Jensen, D.D., Buckley, R.T., Menefee, D.A., Ziegler, K.K., Wood, K.L., Crawford, R.H., 2012. Prototyping Strategies: Literature Review and Identification of Critical Variables. Presented at the 2012 ASEE Annual Conference & Exposition, p. 25.1091.1-25.1091.22.

Dow, S.P., Heddleston, K., Klemmer, S.R., 2009. The efficacy of prototyping under time constraints, in: Proceedings of the Seventh ACM Conference on Creativity and Cognition, C&C ’09. Association for Computing Machinery, New York, NY, USA, pp. 165–174. https://doi.org/10.1145/1640233.1640260

Erichsen, J.F., Sjöman, H., Steinert, M., Welo, T., 2020. Protobooth: gathering and analyzing data on prototyping in early-stage engineering design projects by digitally capturing physical prototypes, in: AI EDAM. Cambridge University Press, pp. 1–16. https://doi.org/10.1017/S0890060420000414

Hannah, R., Joshi, S., Summers, J.D., 2012. A user study of interpretability of engineering design representations. Journal of Engineering Design 23, 443–468. https://doi.org/10.1080/09544828.2011.615302

Jensen, L.S., Özkil, A.G., Mortensen, N.H., 2016. Prototypes in Engineering Design: Definitions and Strategies, in: DS 84: Proceedings of the DESIGN 2016 14th International Design Conference. pp. 821–830.

Jones, D.E., Snider, C., Kent, L., Hicks, B., 2019. Early Stage Digital Twins for Early Stage Engineering Design. Proceedings of the Design Society: International Conference on Engineering Design 1, 2557–2566. https://doi.org/10.1017/dsi.2019.262

Loflin, W.A., English, J.D., Borders, C., Harris, L.M., Moon, A., Holland, J.N., Kasper, F.K., 2019. Effect of print layer height on the assessment of 3D-printed models. American Journal of Orthodontics and Dentofacial Orthopedics 156, 283–289. https://doi.org/10.1016/j.ajodo.2019.02.013

Melenka, G.W., Schofield, J.S., Dawson, M.R., Carey, J.P., 2015. Evaluation of dimensional accuracy and material properties of the MakerBot 3D desktop printer. Rapid Prototyping Journal 21, 618–627. https://doi.org/10.1108/RPJ-09-2013-0093

Motorola, n.d. moto g7 Specifications [WWW Document]. URL https://support.motorola.com/uk/en/solution/MS143891 (accessed 11.16.20).

Moylan, S., Slotwinski, J., Cooke, A., Jurrens, K., Donmez, M.A., 2014. An Additive Manufacturing Test Artifact. J. RES. NATL. INST. STAN. 119, 429. https://doi.org/10.6028/jres.119.017

Otto, K.N., Wood, K.L., 2001. Product Design: Techniques in Reverse Engineering and New Product Development. Prentice Hall.

Reed Doke, E., 1990. An industry survey of emerging prototyping methodologies. Information & Management 18, 169–176. https://doi.org/10.1016/0378-7206(90)90037-I

Savio, E., De Chiffre, L., Schmitt, R., 2007. Metrology of freeform shaped parts. CIRP Annals 56, 810–835. https://doi.org/10.1016/j.cirp.2007.10.008

Shining 3D, n.d. EinScan-Pro+ Multifunctional Handheld Scanner. Products. URL https://www.einscan.com/handheld-3d-scanner/einscan-pro-plus/ (accessed 11.16.20).

Sims-Waterhouse, D., Bointon, P., Piano, S., Leach, R.K., 2017. Experimental comparison of photogrammetry for additive manufactured parts with and without laser speckle projection, in: Optical Measurement Systems for Industrial Inspection X. Presented at the Optical Measurement Systems for Industrial Inspection X, International Society for Optics and Photonics, p. 103290W. https://doi.org/10.1117/12.2269507

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