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Photogrammetry-based 3D scanning for supporting design activities and testing in early stage product development

Sampsa Kohtala[a]*, Jørgen F. Erichsen[a], Ole Petter Wullum[b], Martin Steinert[a]

[a]*Norwegian University of Science and Technology, Department of Mechanical and Industrial Engineering, Richard Birkelands vei 2B, 7491 Trondheim, Norway*
[b]*Norwegian University of Science and Technology, Department of Design, Kolbjørn Hejes vei 2B, 7034 Trondheim, Norway*

* Corresponding author. Tel.: +47-413-58-744; *E-mail address:* sampsa.kohtala@ntnu.no

Abstract

In the early stages of product development and design, physical prototypes are designed and built from varying materials with the aim of providing valuable experience and decision support for the project team. In the era of digitalization, 3D printing has become a common tool that can produce even complex organic shapes. However, methods for developing the required digital models based on the physical prototypes are still often considered a high investment in resources, reserved for later, converging development activities. In this paper, we close the loop from physical to digital, and back to physical prototyping by introducing a proof-of-concept 3D scanning method using open-source photogrammetry algorithms. The feasibility of the approach is determined from two case studies: a designer chair, and customized race steering wheel. The successful results show potential for low-cost, simple, and accurate digitalization in the early stage of product development and design, with the main challenges being the inherent limitations of photogrammetry and the often-required manual editing of mesh.

Keywords: 3D scanning; photogrammetry; prototyping; design; 3D printing

1. Introduction

In product development (PD) and industrial design, both physical and digital 3D models are utilized in the early stages of development and testing. With the increasing availability of 3D printing technology, the investments required for producing complex and organic models have substantially decreased. However, a limitation that remains for producing such models is the process of generating the digital design that is required for using this technology. The most common solutions for developing digital models with complex shapes are computer aided design (CAD) with freeform surface modelling tools and 3D scanning equipment to digitize physical shapes. These tools are often regarded as a high investment, both due to the time required to use them for generating high quality results, and the cost of the equipment and software itself [1]. Consequently, these tools are rarely utilized in the early stages of PD for conceptual design and prototyping, or in the early stages of design. A simple and low-cost method for utilizing 3D scanning is therefore desired, potentially enhancing the design and testing capabilities of designers and product developers.

In industrial design, the use of various types of physical models in the early stages of the process is a tactically important choice to safeguard a bodily experience and in spatial understanding of the interaction between object and user. Typical materials are clay, cardboard, wood, etc. Due to the possibility to interact, these early phase physical design models enable a comprehensive handling of the product's aesthetic (sensory knowledge like the tactile, the visual and the bodily), aspects that CAD can in no way replace. When prototyping with natural materials, such as wood, leather, and clay, it can also be desirable to maintain their surface imperfections as part of the final design [2]. Material-driven design practices utilize the affordance of materials, enabling designers to explore the solution space through tinkering,

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experimenting, and making with different materials, which can additionally lead to spontaneous discoveries [3]. The need for a simple and quick way to digitize these models in the early phase, without having to geometrically construct this again from scratch, is important and much needed.

Early in PD projects, physical prototypes are designed, built and tested with the aim of providing valuable experience and decision support for the project team [4-6]. Such prototypes are valuable for exploring solutions and problems early on, with low cost and high degree of uncertainty. However, concepts and ideas that can only be represented through prototypes that require a high investment in terms of time and cost, e.g. a sophisticated CAD 3D-model, is less likely to be changed during the design process [7]. Hence, exploring tools and methods for producing low-resolution prototypes with simple materials such as cardboard and clay is important to enable more design iterations. Failing to properly prioritize important decisions early on can in turn limit the functionality or the structural integrity of the prototypes and prevent possibilities for testing. By digitizing and 3D printing such concepts through e.g., clay models, it is possible to prototype and test complex and organic shapes. The goal is similar to the efforts by Mathias et al. [8] to accelerate prototyping by combining both low- and high-fidelity prototypes in the iterative design approach.

Common 3D scanning equipment, such as laser or structured light scanners, can be either expensive and complicated or of low resolution. The quality of photogrammetry-based 3D scanning has improved over the last decades due to readily available high-resolution digital cameras, faster computers, and better algorithms [9]. With the prevalence of open-source software, and adequate processing power being common in consumer grade computers today, there is a high potential for using photogrammetry-based 3D scanning in early stage PD without requiring a high investment. Introducing this method to the early stages of PD and design workflows can solve some of the challenges with combining physical and digital prototyping, and can aid in designing, building, and testing complex and organic designs.

The aim of this study is to prototype and test the feasibility (relating to the effort, skill and investment needed) of using low-cost 3D scanning (photogrammetry) with a single digital camera, in the context of physical prototyping and digitalization in the early stage of PD, and to discover how this method can be implemented and used. A proof-of-concept 3D scanning setup is described, and its applications explored by two cases: a real-world industrial design application, where a physical chair design was digitized, and through experimental prototyping of a custom-fit steering wheel. We close the loop from physical to digital and back to physical prototyping and explore the limitations of the method to provide possible areas of improvement for future PD activities and research.

2. 3D scanning method, setup, and pipeline

Photogrammetry has been used in many different areas, such as documenting cultural heritage in 3D [10], prosthetic socket design [11], applications in geoscience [12], and measuring car body deformation in the automotive industry [13]. Although photogrammetry has been viewed as a tedious or difficult process reserved for experts [10], recent improvements and new techniques have simplified the process. Using only photographs of a scene or object from different viewpoints, photogrammetry algorithms can generate a 3D point cloud and mesh. The main techniques used are Structure from Motion (SfM) and Multi View Stereo (MVS). With the increasing affordability of various 3D scanners, such as time of flight, LiDAR and structured light scanners, the main advantage of photogrammetry is that most people already have access to the required hardware and software, as only a digital camera and a computer is needed, with several open-source implementations for the processing readily available. In addition, photogrammetry is not limited in the size of objects that can be scanned [14] and does not require an advanced setup or calibration to produce high quality 3D models, thus enabling customization and automation of the process.

2.1. Open-source photogrammetry algorithms

SfM is the first step when reconstructing a digital 3D model from photographs. We use an open-source, general-purpose (incremental) SfM implementation named COLMAP [15]. This algorithm takes (unstructured) images from different views of the same object (or scene) as input, then calculates camera poses and reconstructs a sparse point cloud of the object as output.

To get a detailed and refined mesh of the scanned object, a dense point cloud is first generated by applying MVS algorithms with the sparse reconstruction (sparse point cloud, images, and their corresponding camera poses) as input. We use two different methods for this approach, where the MVS pipeline by COLMAP has provided good results on bigger datasets and of more difficult and large objects, while OpenMVS [16] is faster and has worked well for smaller and more detailed objects such as clay models. The aim of MVS is to estimate depth and normal data for each pixel in each camera pose reconstructed from SfM [17, 18]. The depth and normal estimates can then be fused from the image space into a dense point cloud. The Poisson method has been applied for reconstructing a surface mesh from the dense point cloud, which is based on the Screened Poisson Surface Reconstruction algorithm [19]. The output from MVS using COLMAP is a mesh with vertex colors, while OpenMVS provides a refined mesh with texture.

Both COLMAP and OpenMVS can be used through the command line interface (CLI) and can thus be easily automated through a scripting language.

2.2. 3D scanning setup

A physical setup has been developed with the aim of simplifying and automating the 3D scanning process. The 3D scanning setup consists of four main components: a digital single-lens reflex (DSLR) camera, photo booth, turntable, and a laptop for control and processing

A Nikon D5300 camera with an "AF-S DX NIKKOR 18-140mm f/3.5-5.6G ED VR" lens has been used for capturing images of the object being scanned. This camera and lens were chosen simply based on what was available at hand when developing the system. The camera is attached to an adjustable arm and connected by cable to the laptop. An open-source CLI tool named gPhoto2 is used to control the camera (i.e. capture and transfer images). Basic camera settings have been set and tuned manually by experimentation to provide sufficient image quality for the 3D reconstruction pipeline, shown in Table 1, while the position and focus is manually adjusted before scanning.

Table 1. Camera (Nikon D5300) settings used for 3D scanning.

Setting	Value	Objective
Shutter speed	1/40 seconds	A fast shutter speed is needed to reduce or prevent motion blur from the continuously rotating turntable during capture.
f-number	9	Preserve details (focus) on the object while keeping the background diffused.
ISO	100	A low ISO is possible with good lighting and is used to reduce noise.
Resolution	2992x2000 pixels	Small image size with normal JPEG quality, providing enough details while reducing processing time and file size.

The main function of the photo booth, shown in Fig. 1, is to highlight the object by keeping the number of features in the background as low as possible, effectively hiding the surrounding environment. This is required for the SfM algorithm to successfully generate a sparse reconstruction, as the scene should ideally be kept static. To reduce possible shadows, we use sheets of self-adhesive matte black vinyl to cover the walls. Consequently, the objects should not contain dark colors that blends with the background. The current setup is also limited to objects smaller than roughly 1 m high and 0.8 m wide.

The turntable is made with a laser cut wooden plate attached to a shaft in a 3D printed housing. A belt transfers motion to the shaft from a stepper motor controlled with serial communication from the laptop through an Arduino Mega microcontroller. The turntable rotates at a constant speed (roughly 2.1 rpm) during the scan to speed up the process, which is limited by the capture and transfer speed of the camera.

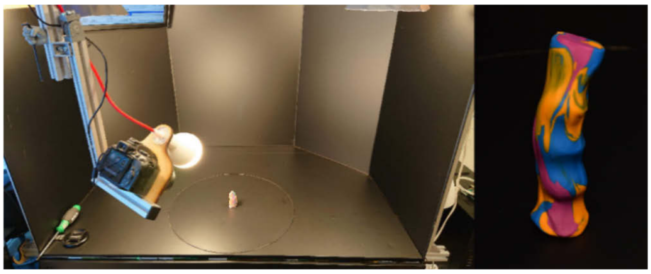

Fig. 1. 3D scanning setup showing the adjustable camera system, photo booth, and turntable, with an example of a captured image to the right.

A laptop with a 6-core Intel Core i9 4,8GHz CPU, a Nvidia GeForce GTX 1050Ti GPU and 32GB memory is used for running the whole pipeline, from scanning the object to reconstructing the 3D model and doing post processing. Some modules (see Fig. 2) of the pipeline are sped up by utilizing the parallel computing capabilities of the GPU. The scanning and reconstruction stages are run through a script, rendering the process fully automatic. For each scan, a timestamped folder is created containing the captured images and results from the reconstruction (point clouds, meshes, textures, etc.). The custom script provides the possibility of adjusting scanning parameters and is used for documenting processing durations.

2.3. Post-processing and 3D printing

The scanned and reconstructed model can be adequate for digital representation and 3D printing, but generally one or more post-processing steps are needed to clean and prepare the mesh further. MeshLab [20] is an open-source mesh processing and editing tool with a graphical user interface (GUI) and is usually the first program we use after a successful reconstruction. MeshLab also provides the possibility to generate a script based on a sequence of filters and operations applied to a mesh, making it possible to automate many of the common mesh editing stages required after a reconstruction (e.g., removing mesh based on color, closing holes, and refining the mesh). The last step using MeshLab is to scale the model by measuring a known distance between two points on the model, and finally exporting the model as an STL (stereolithography) file that can be 3D printed or processed further with other software.

MeshMixer is a free software by Autodesk that has similar functions to MeshLab. When the reconstructed model is a thin surface, MeshMixer can be used for extruding areas of the mesh to apply thickness to the model.

We have also used Siemens NX, a professional CAD software, for integration with CAD models and to apply parametric features to the scanned model. NX also has a freeform surface fit tool for generating a parameterized surface of the scanned model. The model can then be further developed with common CAD procedures or be exported to a STEP (Standard for the Exchange of Product model data) file often used in manufacturing.

Several 3D printing methods and instruments are readily available today. For the cases presented in this paper, we have used FDM (fused deposition modeling) printers with PLA plastic (polylactic acid). A desktop 3D printer (Prusa i3 MK3) is used with the Slic3r Prusa Edition software for slicing the model before printing, while for larger prints we have used the 3DP WorkSeries 400 printer with Simplify3D slicer software.

2.4. Overview of the 3D scanning pipeline and limitations

An overview of the 3D scanning pipeline is given in the form of a workflow diagram in Fig. 2. It highlights the stages going from physical prototyping (e.g., making a clay model) to generating a digital representation of the prototype and back to a physical prototype augmented through the process (e.g., printing the clay model in a stronger material to enable more testing possibilities or adding parametric features to the model). The insights from the new prototype can then be used for improving the initial prototype or iterating new concepts.

There are several well-known limitations of photogrammetry, with the main three being lack of texture, thin structures, and non-Lambertian surfaces [21]. Uniform surfaces with little or no texture cannot be reconstructed as there are no features that can be detected, compared, and triangulated to generate a 3D point cloud. Photo-consistency during the MVS algorithm is usually evaluated from several pixels in the images. Reconstructing thin structures that cover only one or a few pixels can therefore be difficult. Non-Lambertian surfaces (i.e., shiny, or transparent objects) reflects the surrounding environment which the algorithms are generally unable to handle. Capturing intricate objects can also pose a challenge due to areas being occluded from the camera view, which may require the user to capture difficult views manually.

Even though good results can be achieved with the method in different scenarios, scenes, and setups by adjusting camera settings, the limitations of photogrammetry can often cause different modes of failure or defects on the output. A checkpoint after the reconstruction (Fig. 2) is thus needed to determine if and what changes can be applied to improve the result.

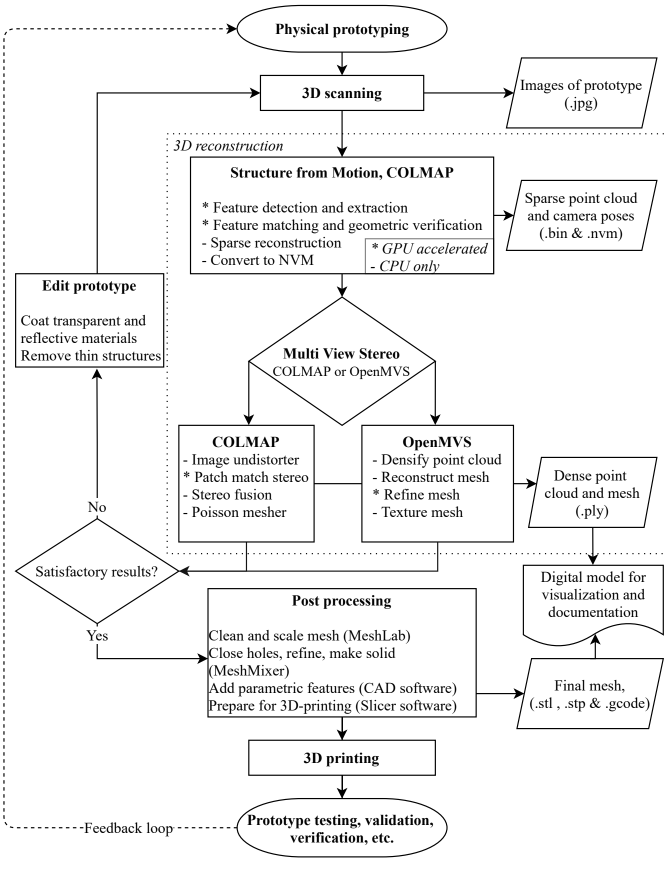

Fig. 2. Workflow diagram of the physical to digital and back to physical prototyping process using 3D scanning (photogrammetry) and 3D printing.

A completely failed reconstruction is often caused by non-Lambertian surfaces for which a reflective or transparent object should be coated (e.g., using paint, chalk spray, clay, or tape) before attempting a new scan. Defects on a reconstructed model are often the result of featureless areas on the physical model that should also be covered with a feature rich texture. The method and workflow illustrated in Fig. 2 will be demonstrated through two practical case examples in the following sections.

3. Case examples from design and PD

The 3D scanning system was tested on two real case examples: one from industrial design and one from PD. The duration along with an assessment of the different stages in the process was recorded to evaluate the effort, skill level and investment needed to use the system. In addition, we assessed both the digital model and the corresponding 3D printed version to qualitatively determine the quality of the output.

3.1. Design case: chair design

A basic exploration of the possibilities of creating a sculptural expression, both visually and functionally (form and comfort, which reflect how we "read" a chair: both with the eye and with the body), on a chair seat without using double-curved surfaces, so this can be produced in ordinary plywood. A tactical choice of using cardboard in the early phase was done both to simulate similar possibilities and limitations that lie in thought-produced material as well as the inherent properties of the sketch material for resilient processes of curved surfaces. This gives shape geometries that are spontaneous and difficult to reproduce in CAD by constructing it from scratch. It is therefore necessary to be able to digitize this form in an easy way during the early phase of the process to be able to verify and further develop the expression, and for milling or printing out ergonomic test models.

The cardboard chair model was scanned with the process described in the previous section. The digitized model was then further processed to generate rendered images of the design, and to export a parameterized version of the model for verification by manufacturers, and for 3D printing a small-scale model for visualization and inspection.

Two alternative iterations of the chair were made from the same artefact using tape to keep the model suspended in different configurations. This was done to show how the process allows iterating slight changes on the model that can influence the overall shape, which is difficult using only digital tools. Additionally, for the sake of enabling physical testing of the concept in terms of sitting comfort, a full-scale version of the initial design was 3D printed in PLA plastic.

3.2. PD case: custom-fit steering wheel prototype

Designing and testing ergonomic shapes for high performance products can demand a substantial effort by the design team, in addition to the involvement of the user. With an iterative and rapid prototyping mindset, we attempt to explore how the 3D scanning process can introduce new possibilities for prototyping complex and organic shapes through developing a custom-fit steering wheel. The prototype is constructed using accessible clay (play dough) to quickly approximate the natural position and shape of the users' (in this case one of the authors') grip on a steering wheel concept found online, made by Souissi [22]. The generic steering wheel shape was laser cut from a medium density fiberboard (MDF) plate and used as the base for the custom-fit handles.

4. Results

4.1. Chair design

15 out of the 29 captured images were automatically selected by the SfM algorithm for further processing. The initial mesh was not complete with the pre-set Poisson parameters, and had to be re-iterated using a higher point-weight. Parts of the background remained in the final mesh, which were automatically selected and removed in MeshLab based on its darker vertex-colors compared to the chair. The number of faces was reduced before manually scaling the model based on a known measurement.

MeshMixer was used to add thickness and generate a solid model. The shell mesh was additionally processed in Siemens NX with the freeform surface fit tool to automatically generate a parametric model of the shape. The generated surface had a square boundary, which was corrected by intersecting the fitted surface and the solid model from MeshMixer. The parameterized surface model of the chair was then given a thickness of 9mm in NX before exporting STEP and STL files for further interpretation and 3D printing. The process of digitizing the chair model along with task descriptions and durations are shown in Table 2.

Table 2. Steps of the 3D scanning process for the chair prototype.

#	Task	Description	Duration [min:s]
1	Scanning the cardboard chair	Adjusting the camera position and focal length, before starting the automatic capturing process.	1:30
2	Reconstruction*	Using COLMAP for both the sparse and dense reconstruction.	26:52
3	MeshLab script*	Removing dark-colored mesh using the conditional selection tool and reducing the number of faces.	0:05
4	Manual mesh editing	Scaling the model, adding thickness, smoothing, and exporting an STL.	4:26
5	Surface estimation*	Applying a freeform surface fit to generate a parameterized model, with an average and max error of 0.22mm and 3.66mm, respectively.	5:24
6	Surface extraction	Extracting the chair by intersecting the parameterized surface with the extruded shape, then applying a thickness of 9mm to the surface.	2:34
7	Slic3r PE	Preparing the model for printing.	1:05
	Total		41:56

* automatic process

The two other iterations of the chair model followed the same approach as described in Table 2. Along with the original chair model, they were rendered in high quality images with different materials in NX as shown in Fig. 3.

Fig. 3. Rendered images of the three different 3D scanned chair iterations. The initial unaltered prototype from Table 2 is in the middle.

4.2. Custom-fit steering wheel prototype

Different colored clay was mixed to improve the reconstruction by increasing the number of features that can be detected by the algorithm. The natural and organic shape of the users' hand gripping the steering wheel was captured by squeezing the clay on the steering wheel. To capture the object in one scan, it was placed standing on the middle of the turntable supported by clay. The support was included in the reconstructed model and had to be manually removed in MeshLab. Holes resulting from removing the support structure were closed using MeshMixer before generating and exporting a solid model. NX was used to add the required parametric features on the scanned model. The added features were created to enable assembly of the 3D printed handle with the MDF steering wheel. The process including the duration of each stage is provided in Table 3, with several stages of the process displayed in Fig. 4.

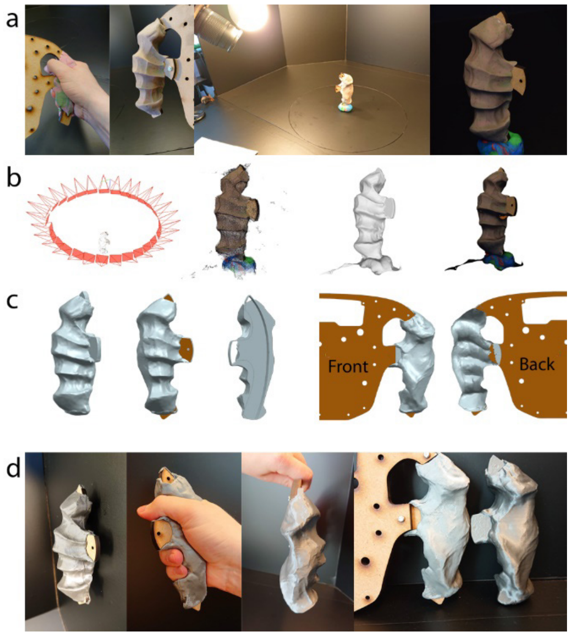

Fig. 4. Several stages of the process of prototyping a custom-fit steering wheel, including (a) clay shaping and scanning, (b) reconstruction, (c) adding parametric features, and (d) showing the 3D printed results.

Table 3. Steps of the 3D scanning process for the custom-fit steering wheel.

#	Task	Description	Duration [min:s]
1	Clay shaping and scanning	Mixing three different colors of soft clay, then shaping and fitting the clay before starting the scan.	6:14
2	Reconstruction*	Generating a sparse point cloud with COLMAP, then a dense point cloud and a refined mesh with OpenMVS.	2:54
3	Mesh editing and refinement	Removing the mesh generated of the clay support, closing holes and refining the mesh, before scaling the model based on a known distance.	4:47
4	Adding parametric features	Using NX to subtract the steering wheel base-structure from the scanned model.	9:53
5	Slic3r PE	Preparing the model for printing.	0:54
	Total		24:42

* automatic process

5. Discussion and conclusions

The feasibility of utilizing and incorporating photogrammetry-based 3D scanning in early stage PD has been explored and demonstrated through two practical case examples: one in the context of design and one in the context of PD. In the first case, the tactical choice by an industrial design expert to develop a physical chair model using cardboard introduced the importance of including a simple and quick way of digitizing physical models in the early design stage, as digital models can support communication and feedback from stakeholders and is a requirement for using 3D printing technology. A complex yet rapid clay model prototype, developed in the second example, required 3D scanning to enable further testing and validation through a 3D printed version. Both models were successfully digitized with the proof-of-concept 3D scanning setup utilizing open-source SfM and MVS algorithms. A subjective visual and tactile evaluation of the 3D printed reproductions suggests the quality to be sufficient for prototyping and testing, although a more analytical approach is needed to further validate the accuracy of the method. The tipping point between using the method compared to conventional modelling techniques, e.g., what level of dimensional complexity should be considered to favor one approach over the other, is difficult to define. However, the use of curved and non-symmetrical surfaces in our cases, along with an iterative and rapid prototyping mindset, led us to prefer the 3D scanning approach.

While the scanning process is simple and the automatic reconstruction algorithms being able to generate complete 3D models, some of the post-processing steps still require a certain degree of effort and skill depending on the desired output. For example, minimal mesh editing was needed for 3D printing a simple version of the clay model, while adding parametric features to both models required substantial CAD integration to enable more in-depth interpretation, validation, and development.

With the prevalence of open-source software constantly being developed and improved by the community, and the method only requiring unstructured images of the object as input, photogrammetry-based 3D scanning has shown great potential as a low-cost, fast and versatile tool for augmenting and supporting development activities in early stage PD and design.

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