Title:
An Optimized Workflow for Material Texture Reconstruction

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Introduction:

Prototyping is a crucial phase during product development that allows designers to evaluate and refine concepts through iterative processes [1]. Projection-based spatial augmented reality (P-SAR) has significantly enhanced this phase by enabling mixed prototyping, which combines tangible physical prototypes with virtual enhancements [2]. This approach facilitates real-time manipulation of perceptual features, such as surface material appearance and shape deformation, without requiring physical displays or additional electronics. While P-SAR technology has the potential to accelerate design iterations, reduce costs, and improve collaborative communication, it faces critical barriers to widespread adoption. These include complex setups, the expertise required for content creation, and the challenges of realistically reproducing material surfaces [3]. Additionally, the reliance on technical experts and professional-grade equipment for scanning and digitising physical materials increases the time and cost of content creation, diminishing the advantages of mixed prototyping [4]. Addressing these issues requires more intuitive and efficient material scanning tools and workflows that ensure accurate representation while reducing the complexity of the digitisation process.

Current material scanning systems are predominantly based on the photometric stereo method. This computer vision technology captures detailed surface geometry and texture information by analysing how materials reflect light under different lighting conditions [5]. While professional-grade scanning equipment offers high accuracy and reliability, its high costs and closed-source workflows limit accessibility and customisation. Alternatively, outsourcing to commercial service providers introduces delays and increases carbon emissions due to transportation [6]. Simpler setups, such as those using standard tripod-mounted cameras, offer cost-effective options but often lack stability and repeatability due to their rudimentary configurations [7]. These limitations across existing methods highlight the need for material scanning workflows that are scalable, efficient, and user-friendly, particularly in the context of prototyping and design applications.

To address these challenges, this work proposes an optimised workflow for scanning materials and generating their PBR (Physics-Based Rendering) textures, enhancing the realism of mixed prototypes in subsequent P-SAR applications. Specifically, the workflow targets a variety of materials commonly used during the product prototyping phase, such as fabrics and plastics. It begins with a custom-designed scanner that can be configured to the specific properties of the material being scanned. The workflow integrates photometric stereo-based raw image data acquisition with an adaptable software post-processing pipeline that outputs albedo and normal maps, with optional extensions for additional maps as required. Experimental results on several fabric samples demonstrate that the proposed workflow effectively balances cost, efficiency, and accuracy in material digitisation. This solution can potentially drive broader adoption of P-SAR technology, advancing prototyping and design processes in product development.

Proposed Workflow:

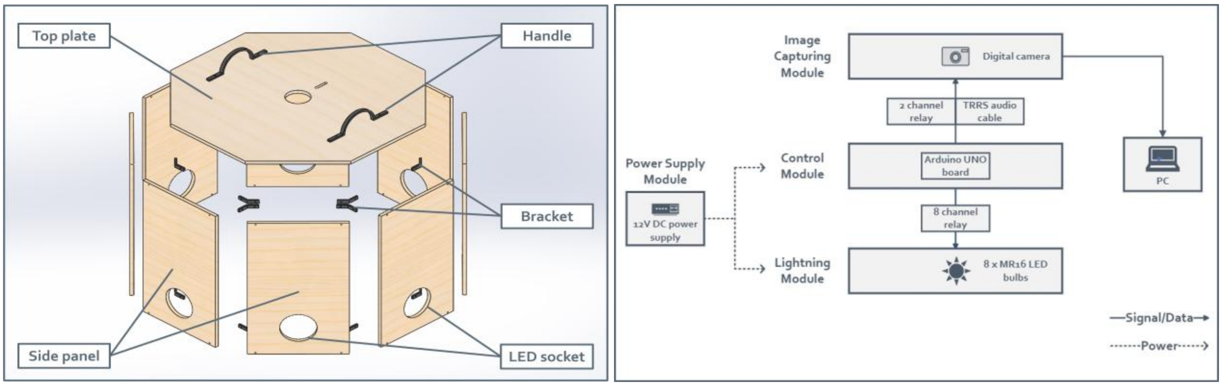
Creating mixed prototypes for P-SAR applications requires accurate material representations, but current approaches present significant obstacles for users. One standard option is outsourcing to commercial service providers to obtain customised material textures, which involves high economic and time costs due to communication, production, and delivery processes [6]. Alternatively, creating material textures in-house often leads to inconsistent quality due to the lack of accessible and reliable tools [7]. These limitations arise from challenges in the hardware and software stages of material scanning. To address these issues, this work proposes a comprehensive material digitisation workflow that includes the setup of a low-cost, custom-designed scanner and a series of steps for generating PBR textures based on data acquired from the scanner.

The proposed workflow is developed through the following steps:

- scanner design and setup;
- camera parameter selection and calibration;
- raw data acquisition and processing;
- texture quality assessment.

Scanner design and setup

The scanner body is constructed using laser-cut wooden panels and 3D-printed connectors, offering low manufacturing costs and easy assembly. The structure is divided into two main parts. The lower section comprises eight side panels that provide support and feature pre-drilled holes for mounting LED light assemblies. The upper section includes a top plate and a camera mount, designed to block ambient light and securely hold the camera in position. The scanner's electronics, controlled by an Arduino microcontroller, automate the acquisition process by managing eight LED lights' on/off states and synchronising with the camera shutter [8]. All electronic components are powered by a 12V DC power supply, ensuring stable operation. The structure and circuit logic of the scanner used in this work are illustrated in Fig. 1, and the detailed design can be customised based on requirements.



(a) (b)

Fig. 1: Schematic of the custom scanner design: (a) exploded view of the scanner structure, (b) circuit diagram illustrating the control logic for LEDs and the camera.

The LED lights used are of the MR16 specification, with specific models selected based on their high colour rendering index (CRI) above 95 and a correlated colour temperature (CCT) of 6000K to accurately reproduce the hues of scanned materials [9-11]. LEDs with minimal beam angles are employed to simulate ideal parallel light sources. For materials with varying sizes and thicknesses, adjustable LED holders or customised side panel hole positions are used to maintain optimal illumination angles, ensuring an incidence angle between 15° and 60° to the material surface [13-14].

A standard consumer-grade digital camera is mounted on the top plate via a tripod head, allowing precise alignment. The camera lens has a cross-polariser, while linear polarisers are attached to all LED lights. Adjusting the polarisers to the correct angles minimizes glare caused by the illuminated material surface, enabling accurate albedo colour capture [15]. This configuration ensures the reliability and quality of the raw data, forming the foundation for subsequent processing steps.

Structural stability was considered during the design, while the scanner was constructed using low-cost materials. A simplified finite element simulation was conducted to verify that the frame would not undergo significant deformation under static load.

Camera parameter selection and calibration

Before scanning, the camera is mounted on a tripod head and aligned with the hole in the top plate to ensure accurate positioning. The camera is set to manual exposure mode (M) and maintains fixed exposure parameters throughout all scanning sessions—a standard configuration for most materials' exposure and consistency [16]. Due to the high brightness of the LED lights, ISO is set to its lowest value to minimise noise. The aperture is initially set two stops below its maximum value and gradually reduced until all material details are focused. The shutter speed is adjusted to be faster than the safe shutter value, determined as the reciprocal of the lens's 35mm equivalent focal length, and depends on the chosen LED brightness. This study's selected settings are ISO: 200, aperture: f/11, and shutter speed: 1/60″. Additionally, the camera operates in manual focus mode (MF), with the focal point locked during the scanning process.

Initial colour calibration is performed through hardware methods, including X-Rite ColorChecker tools under the same lighting and exposure conditions as the scanning workflow [17]. A neutral white object (e.g., X-Rite ColorChecker White Balance) is photographed to set a custom white balance for the camera, which is maintained for all subsequent scans. A colour reference chart (e.g., X-Rite ColorChecker Classic) is photographed under the same setup to create a DNG camera profile with software like X-Rite ColorChecker Camera Calibration. This profile standardises the camera's colour response and is applied to all raw images.

Further colour calibration is achieved using a three-dimensional lookup table (3D LUT) method [18]. Under the same setup conditions, the camera captures 512 colour samples selected from the RAL DESIGN SYSTEM plus colour system. The captured samples' L, a, and b values in the CIELAB colour space are compared to their actual reference values to construct an initial lookup table. Colours not corresponding to sampled points are calculated using trilinear interpolation within the colour space. This lookup table is applied to all images already calibrated with the DNG camera profile, enabling per-pixel correction of L, a, and b values for enhanced colour accuracy.

Raw data acquisition and processing

After completing the camera setup and calibration, the material to be scanned is placed flat on the bottom of the scanner. Once powered on, the system operates automatically under Arduino control. To capture colour information, all eight LED lights are turned on simultaneously, and the camera takes one photo before the LEDs are turned off. For surface normal measurement, the LEDs are sequentially activated in a counterclockwise order, with one photo taken per LED, resulting in eight photos. The scanner captures nine images as raw data during a scanning session.

The captured images are corrected for colour using the previously established calibration methods and then imported into 3D software for post-processing. To balance ease of use and functionality, Adobe Substance 3D Designer was chosen for its comprehensive support of the PBR technique. Its node-based workflow provides high flexibility and customisation, while Python scripting allows task automation. Furthermore, its broad compatibility with major 3D engines and AR systems ensures seamless integration of the generated texture maps into downstream applications.

A custom pipeline was created within Substance 3D Designer and packaged into a reusable node-based compositing graph. This pipeline includes steps such as image cropping, colour equalisation, photometric stereo-based reconstruction, and texture tiling. Node parameters can be adjusted based on the properties of the material being scanned, such as wood, fabric, or plastic. The pipeline takes nine images as input: one with full illumination for colour reconstruction and eight with directional lighting for surface normal reconstruction. The outputs include an albedo map and a normal map based on the PBR-Metallic Workflow. Additional maps, such as roughness or height maps, can be generated as needed. These texture maps are optimised for rendering digital materials in various 3D engines, such as Unity.

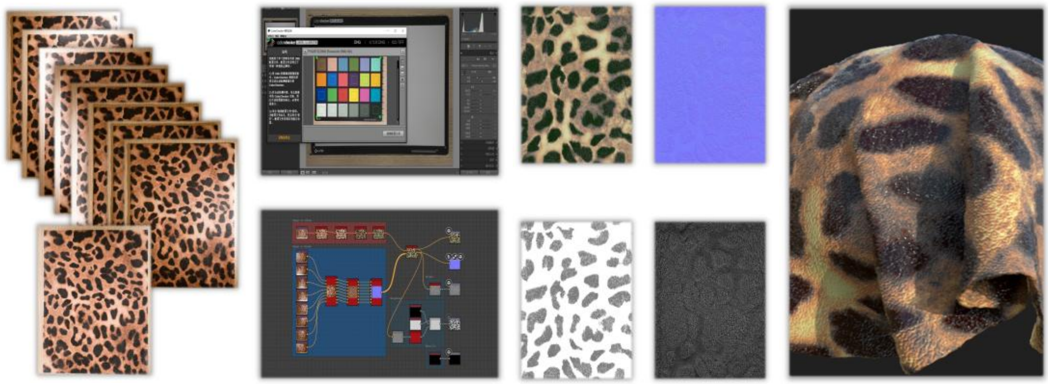
Texture Quality Assessment

In this work, material digitisation accuracy refers to the fidelity of the generated albedo and normal maps, which are the direct outputs of the photometric stereo-based reconstruction. Specifically, albedo accuracy is defined as the correctness of recovered diffuse surface colour information; normal accuracy is defined as the geometric fidelity of surface orientation.

Given that scanned materials typically lack digital ground truth for direct comparison, and considering the variability in hardware (e.g., scanner structure) and software parameters (e.g., post-processing pipeline), this work proposes an indirect evaluation method based on standard reference samples [18-19]. The quality of the workflow's two primary outputs—colour reconstruction (albedo map) and surface normal reconstruction (normal map)—is quantitatively assessed.

The fidelity of the albedo map is evaluated using a standard colour chart, such as the RAL DESIGN SYSTEM plus, ensuring consistency with the colour calibration process. A set of colour samples, distinct from those used during calibration, is scanned to generate corresponding single-colour albedo maps. The colour difference (ΔE2000 metric) between the reconstructed albedo maps and the actual values of the colour samples is computed. ΔE2000 is selected to consider human visual sensitivity to different colours [20]. The resulting ΔE2000 values are analysed to quantify the colour reconstruction accuracy.

The fidelity of the normal map is evaluated using a 3D-printed reference surface with known normal directions defined in CAD modelling software. The reference surface is scanned, and the resulting normal map is converted into surface normal vectors. The angular deviation between the reconstructed normals and the ground truth normals is calculated and analysed. This clearly measures the normal map's accuracy in representing the surface geometry. Based on the evaluation results, hardware configurations (e.g., scanner setup) and software parameters (e.g., node settings in the post-processing pipeline) can be adjusted to optimise the workflow. Fig. 2 presents the representative images for the main steps of the proposed method.



(a) (b) (c) (d)

Fig. 2: Steps of the proposed material scanning workflow, demonstrated with a leather fabric sample: (a) captured raw images with the scanner; (b) processing pipeline in the software; (c) generated PBR textures; (d) rendered digital material.

Conclusions:

This work presents a comprehensive and low-cost workflow for scanning physical materials and generating their digital counterparts. It combines hardware design, camera configuration, robust colour calibration, and a structured reconstruction pipeline to produce accurate PBR texture maps. The system supports full user customisation and has been validated through tests on fabric samples, demonstrating its ability to generate reliable albedo and normal maps. While these materials served as the primary test cases, the workflow applies equally to materials commonly found in CAD-based product design, such as plastics or painted surfaces, where visual fidelity plays a key role in early-stage evaluation. Designed to support projection-based mixed prototyping, the system enables designers to preview realistic surface textures efficiently. Future work will focus on further automation, including material-specific parameter presets, to enhance usability across broader application contexts.

Acknowledgements:

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