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Spatial augmented reality for product appearance design evaluation

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Abstract

Augmented reality based on projection, called "Spatial Augmented Reality (SAR)", is a new technology that can produce immersive contents by overlapping virtuality and real-world environment. It has been paid attention as the next generation digital contents in media art and human–computer interaction (HCI). In this paper, we present a new methodology to evaluate the product appearance design more intuitively by means of SAR technique. The proposed method first projects the high-quality rendered image considering the optical property of materials onto the mock-up of a product. We also conduct a projector-camera calibration to compensate a color distortion according to a projector, a projection surface and environment lighting. The design evaluation methodology we propose offers more flexible and intuitive evaluation environment to a designer and user (evaluator) than previous methods that are performed via a digital display. At the end of this research, we have conducted a case study for designing and evaluating appearance design of an automobile.

Keywords: Computer-aided appearance design; Methodology on design evaluation; Projection mapping; Spatial augmented reality; Realistic material modeling

1. Introduction

Augmented reality is a Human–Computer Interaction technique that shows a real-world environment by adding virtuality and it is used in various fields, including industries, medical care, education, entertainment, and mobile applications. According to Azuma et al. [1], augmented reality has to satisfy three conditions: a combination of reality and virtuality, real-time operation and interaction, and a 3-D real world. Unlike virtual reality, in particular, augmented reality provides computer-generated virtual information combined with the real world so that users can interact with augmented reality in accordance with their senses and recognition [2].

Unlike early-stage augmented reality that provided virtual content combined with the real world through digital displays, such as see-through Head Mounted Displays (HMDs), mobile displays, and computer monitors, today's augmented reality can exhibit virtual digital objects on the physical space through Spatial Augmented Reality (SAR) technology introduced by Raskar [3–4]. SAR can maximize user immersion more than existing augmented reality by projecting a variety of information combined with virtual content onto real-world objects. SAR is also called projection mapping because it augments content through a beam projector's projection on an actual object.

Media façades that use projectors are the focus of a recent trend as new media, and such façades are actively used for the promotion of new automobiles, shoes, and clothing. For SIGGRAPH 2013, which was held in the US, NVIDIA, Christie, and RTT presented an interactive SAR application in which a high-quality rendered image of an automobile was projected on a car model, and the testers were able to simulate its appearance according to their preferences [5]. Such technology provides more realistic effects than conventional promotion methods, such as catalogs or Websites, and at the same time, it has the advantage of using spaces more efficiently. Based on such advantages, this study proposes an innovative framework that can help with product appearance design evaluations.

In addition to the quality, performance, and price of a new product, its design has become an important factor for client

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decision-making. Thus, companies pursue innovation even from the early design phase of a product by hiring expert designers, who continuously attempt to understand customer design preferences through surveys and market research. Therefore, in the product development phase, esthetic designing has become an essential process that is effectively assessed without making a real physical prototype, and which reflects the immediate feedback of evaluators. Fig. 1 shows uniquely designed products currently released in the market. Unlike products of the past, today's products with unique design are more popular; therefore, conventional design techniques have limitations in expressing complex and special materials and patterns.

The proposed platform consists of (i) a bidirectional reflectance distribution function (BRDF)-based computer-aided appearance design that was introduced by Kim and Lee [6] and (ii) an evaluation process through projection mapping. However, unlike Kim and Lee's design [6], which is limited to opaque materials (metal, plastic, etc.), our platform extends its use of product exterior materials to translucent materials (PVC, wood, etc.). Furthermore, it provides an environment in which the product appearance design can be evaluated intuitively because it can visualize the design on the product model by undergoing a color correction process according to the reflectance of the projection surface. The main contribution of this research is to propose a novel methodology for interactive design evaluation on top of the related element technologies. Our methodology has the following advantages:

- It saves time and cost required in product development because evaluations are conducted in advance in the design phase without producing a physical prototype.
- It is possible to exhibit various designs of a product similar to real ones without the limitations of space.
- It provides a more intuitive and flexible environment than a design evaluation using a digital display.

The remainder of this paper consists of the following sections: Section 2 explains the S/W (software) and H/W (hardware) system configuration required for the proposed system; Section 3 describes the methodology for product appearance design; Section 4 explains the projector-camera color correction for projection mapping; Section 5 presents the experimental results; and Section 6 introduces case studies conducted on automobile design evaluations and provides our conclusion in Section 7.

2. System configuration

Fig. 2 and Table 1 show the system configuration and H/W specification. The system consists of a beam projector, a computer, a camera and a mock-up of a product as the projection surface. As shown in Fig. 3, the proposed framework is divided into two parts: *computer-aided appearance design,* and *design evaluation based on SAR.*

In the first stage, once a concept of a new product is given, the computer-aided appearance design of a product is performed using either our material database or measurement data for BRDF or BSSRDF. The second phase is to visualize the computer-simulated images on a mock-up of the product by the projection mapping technique. Designers or customers are able to evaluate a new appearance design and to change the

Fig. 1. Several examples of product appearance design: (a) wood laptop, (b) matted car, (c) metal smart phone, and (d) patterned refrigerator.

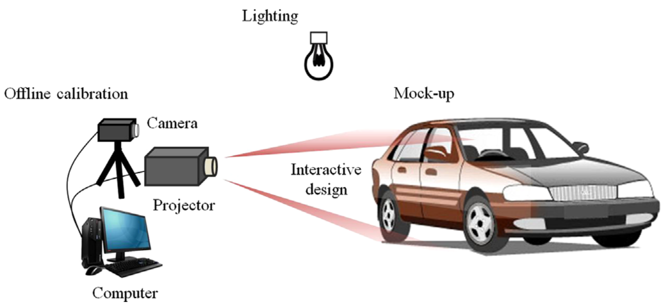

Fig. 2. Hardware configuration of our system.

Table 1
Hardware specification.

Components	Company	Specification
Camera	Cannon MarkII	Resolution 1728 × 1152
Projector	Optoma EW865	Resolution 1280 × 800
		Contrast 4000:1
Computer	–	Dure core CPU 2.66 GHz, 3 GB

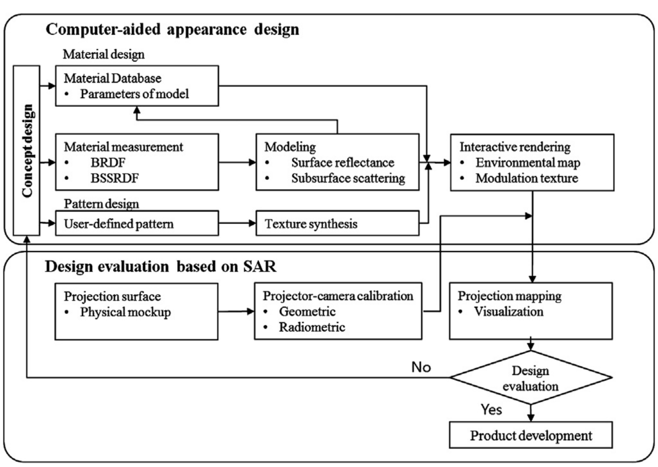

Fig. 3. The proposed SAR-based appearance design framework for a new product development.

appearance color and material of the product until they are satisfied.

To realistically model the reflectance characteristics of opaque and translucent materials, we use the "realistic material modeling" technique that we proposed in our previous studies [7–10]. To project a high-quality rendered image without distortion, our method can perform projector-camera correction depending on the characteristic of a projection surface, and simulate the final appearance design of a product. For faster calculation, we approximated the environment lighting as simply as possible.

3. Product appearance design

The appearance of a product delivers diverse feelings depending on its material and color as well as its shape; therefore, appearance should be designed in consideration of the material that will be used. In this research, product appearance is simulated by optical properties of material which are defined by the BRDF (surface reflection) and BSSRDF (subsurface scattering); furthermore, we measured the BRDF and BSSRDF by material to enhance simulation accuracy.

BRDF is a function that presents the proportion of light that is reflected from a point by angle for an incident light. The isotropy BRDF f_{BRDF} can be presented as follows:

$$f_{BRDF}(\theta_{in}, \theta_{out}, \phi_{diff}) = \frac{dL_{out}(\theta_{out}, \phi_{diff})}{dI_{in}(\theta_{in}, \phi_{diff})} \tag{1}$$

where (θ_{in}, ϕ_{in}) is the direction of the incident light, $(\theta_{out}, \phi_{out})$ is the direction of the reflective light, ϕ_{diff} is an angle between ϕ_{in} and ϕ_{out}, I_{in} is the irradiance of the incoming light, and L_{out} is the radiance of the outgoing light. The BRDF is suitable for representing the surface appearance of opaque materials such as metals and plastics, since it takes only reflection occurring on a surface into consideration.

On the other hand, BSSRDF f_{BSSRDF} is a function that presents the proportion of light that leaves from point x_o after subsurface scattering for the light incident on point x_i. It indicates a model for the transport of light through the subsurface that is suitable for representing the scattering of

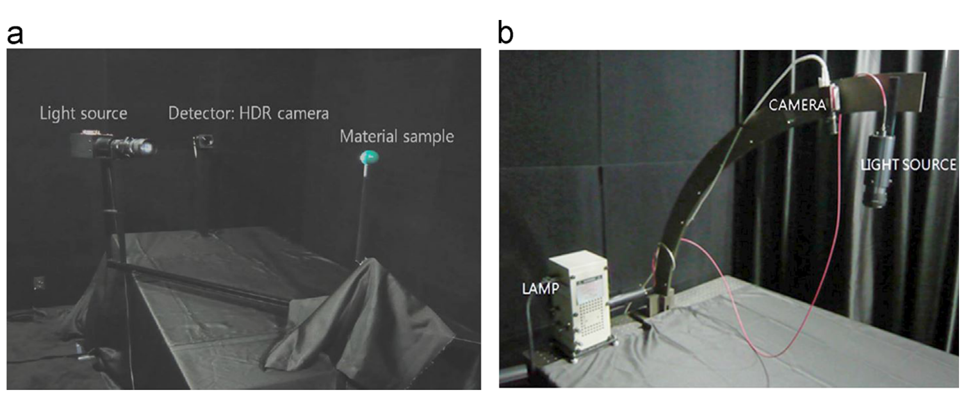

Fig. 4. Material measurement system: (a) BRDF measurement system [7] and (b) BSSRDF measurement system [9].

translucent materials such as PVCs and marbles:

$$f_{BSSRDF}(x_i,\theta_{in},\phi_{in},x_0,\theta_{out},\phi_{out})=\frac{\mathrm{d}L_{out}(x_0,\theta_{out},\phi_{out})}{\mathrm{d}I_{in}(x_i,\theta_{in},\phi_{in})} \qquad (2)$$

The previously developed BRDF (Fig. 4(a)) [7] and BSSRDF (Fig. 4(b)) [9] measurement systems are used to measure optical characteristics of materials. Because measured data by material is stored in a database, repetitive measurements are not required, and the measurement process is required for new materials only one time. It is extremely efficient in terms of data reusability and can be useful not only for product appearance design, but also for computer graphics such as film and games that require high-level rendering.

Material reflectance properties can be obtained through measurements, and they can also be modeled with a predefined reflectance model and its corresponding parameters. In this study, part of the measured data is fitted to the model to obtain material parameters. Such a model fitting method substantially increases modeling speed and accuracy in comparison with a designer's manual modeling, and provides consistent material parameters.

For BRDF models that represent surface reflection, we use Cook–Torrance [11], Phong [12], Ward [13], Blinn–Phong [14] models, and more, and for BSSRDF models that represent subsurface scattering we use Di-pole [15], Multi-pole [16], and P3 [9] models. BRDF material parameters vary by model, but the common parameters are specular reflection, diffuse reflection, shininess, and roughness.

Fig. 5 shows the interactive material rendering S/W developed by our research team. With the parameter-based material modeling and our material database, appearance design with various material textures can be performed.

Fig. 6(a) shows the results of rendering an automobile model applied with the same color, but a variety of opaque materials, and Fig. 6(b) shows the results of rendering an MP3 model applied with a variety of opaque and translucent materials. With the proposed method, designers and users can change materials easily in various environments and evaluate appearance by material. Designers and users can find their design preferences in the early design phase without producing a physical prototype, thus minimizing common trials and errors in the design process.

4. Projector-camera color correction

To obtain an ideal result from projecting a high-quality image rendered by color and material onto a colorless projection surface of a product, a correction process is necessary for the image projected from the beam projector. Fig. 7 shows the process of projecting Image I that was transformed into Image C according to the characteristic of the projector g with respect to wavelength, the ambient light a, and the camera response h. Grossberg et al. [17] proposed an offline color correction method that uses six images to correct the output image for accurate color projection.

The irradiance C, which is obtained by the camera, is modeled by four factors—the non-linear response P for the intensity of the projector, the spectral response of the projector w, the reflectance on a projected surface s, and the spectral response of the camera q—as follows:

$$C=\int(a(\lambda)+Pw(\lambda))s(\lambda)q(\lambda)\mathrm{d}\lambda \qquad (3)$$

where λ is the wavelength. Since this model is only considered in a single channel, we need to generalize for the case of multiple color channels. In [17], the above equation is formulated simply using the color mixing matrix V as follows:

$$C=VP+F \qquad (4)$$

$$C=\begin{bmatrix}C_R\\C_G\\C_B\end{bmatrix},\quad V=\begin{bmatrix}V_{RR}&V_{RG}&V_{RB}\\V_{GR}&V_{GG}&V_{GB}\\V_{BR}&V_{BG}&V_{BB}\end{bmatrix},\quad P=\begin{bmatrix}P_R\\P_G\\P_B\end{bmatrix},$$

$$F=\begin{bmatrix}F_R\\F_G\\F_B\end{bmatrix} \qquad (5)$$

where V is the mutual couplings by color channel between the projector and the camera, and F is the contribution of environmental lighting a in the scene to camera irradiance.

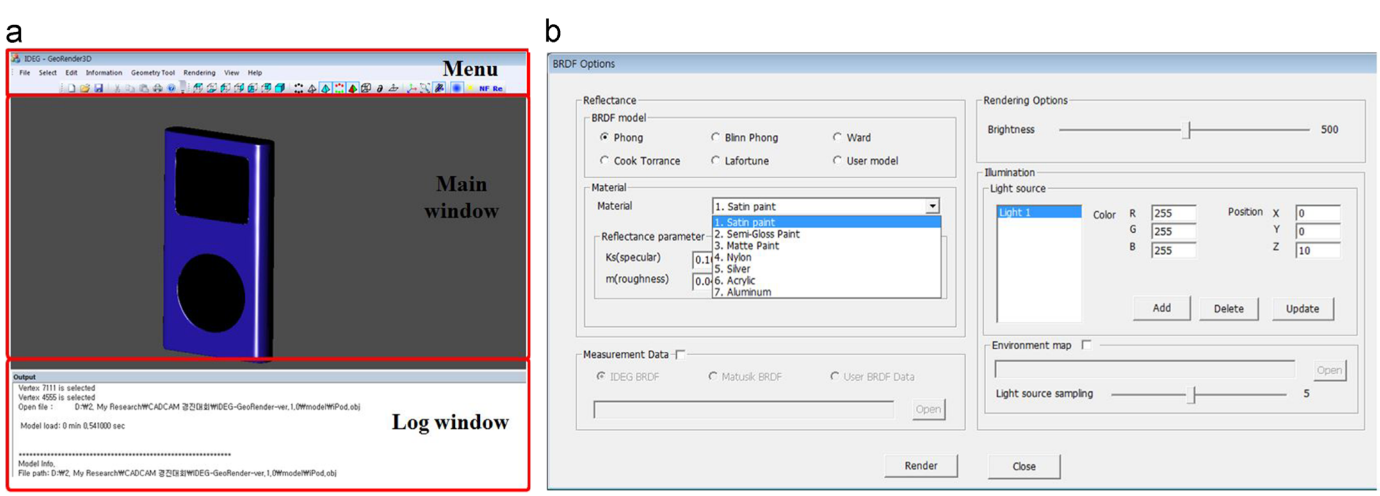

Fig. 5. An interactive appearance design S/W we developed: (a) rendering S/W and (b) dialog for BRDF option.

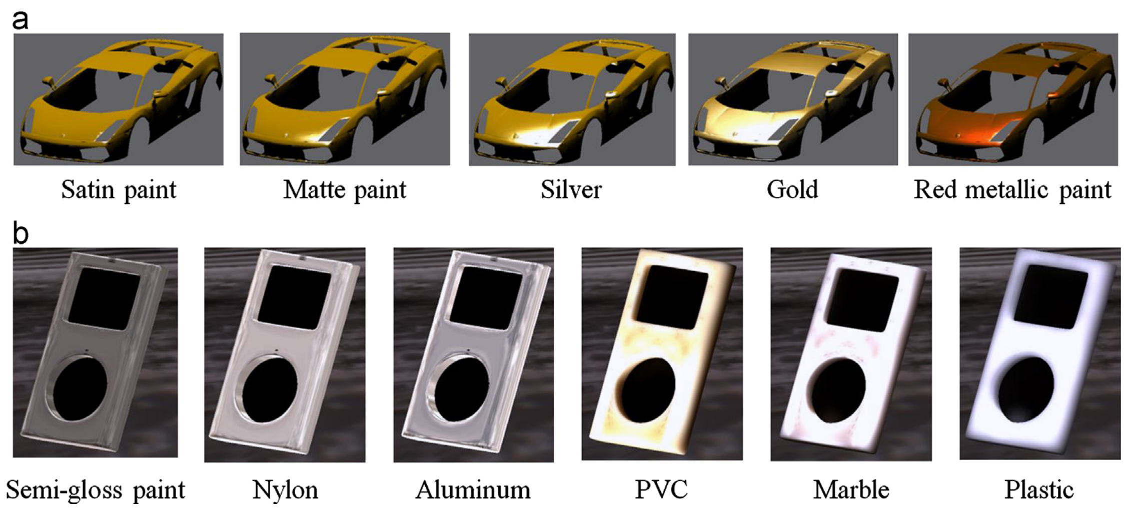

Fig. 6. Rendering results for a car model (a) and an MP3 model and (b) with different materials.

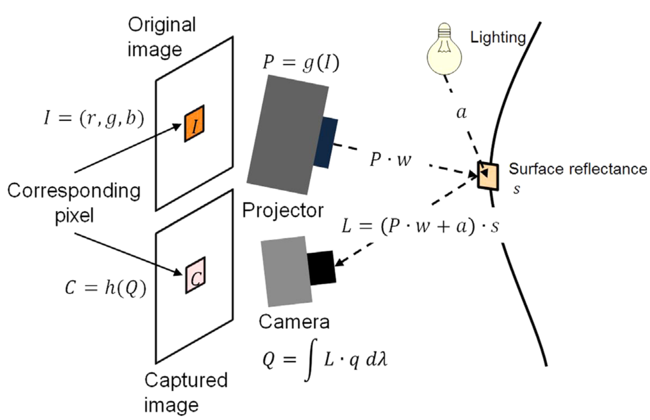

Fig. 7. The dataflow pipeline for a projector-camera system.

Grossberg et al. [17] defined the matrix $\tilde V=VD^{-1}$, which is converted independently of channels, where D is the diagonal matrix with diagonal entries V_{RR}, V_{GG}, V_{BB}; moreover, using two images for R, G, and B, respectively, by channel, Grossberg et al. derived the separated color $\tilde C$, where each term in Eq. (4) was multiplied by $\tilde V$:

$$\tilde C = Dp(I)+\tilde F \tag{6}$$

Where $\tilde C=\tilde V^{-1}C$ and $\tilde F=\tilde V^{-1}F$, and each channel finally becomes independent of the other channels as follows:

$$\tilde C_K = V_{KK}p_K(I_K)+\tilde F_K \tag{7}$$

where K is the color channel.

Then, to consider the non-linearity of the projector, its invariant value N_K is newly defined by two difference images between the gray scale pattern of Fig. 8(f) and the bright gray (d), and a dark gray (e).

$$N_K=\frac{\tilde C_{K,U}-\tilde C_{K,S}}{\tilde C_{K,T}-\tilde C_{K,S}} \tag{8}$$

where $\tilde C_{K,U}$, $\tilde C_{K,T}$, and $\tilde C_{K,S}$ are the values of the measured irradiance in Fig. 8(f), (d), and (e), respectively, which are multiplied by $\tilde V^{-1}$. Therefore, the relationship ρ_K between N_K and I_K of the intensity of U can be defined. ρ_K is a monotonic increasing function calculated using Nadaraya–Watson's non-parametric regression [18].

From the aforementioned relationship, the projection value I, which has to be substituted for an ideal color C, can be calculated as follows:

$$I=\rho\left(\left(\tilde V^{-1}C-\tilde C_S\right)./\left(\tilde C_T-\tilde C_S\right)\right) \tag{9}$$

where ./ represents the division by component.

For the rendering result of the appearance design image C, the to-be-projected image I can be calculated by Eq. (9) for distortion-free projection. Fig. 9 shows the original image on the actual monitor, the uncorrected projection image, and the corrected projection image in order to evaluate the result of correction. This shows that the image distorted was corrected properly by Eq. (9).

5. Experimental results

In this section, the computer-simulated result is compared with an actual material sample in order to evaluate whether the proposed technique express the unique feel of a material. Our experiment has been conducted in a dark room to restrict the ambient lighting condition as simple as possible. The size of the mock-up that is used as the projection surface is 50 mm in diameter, and the computer-simulated result is projected on this surface of a diffuse gray color from about 2.5–3 m away. Fig. 10 shows visual comparisons between the material sample (left) and the result of projection-mapping the rendering result on the model (right). The result is obtained from projecting the various rendered images on the same sphere sample, but each color is properly corrected, thus delivering the characteristics of the appearance of each sample well. Solid paints (a–c) are well fitted with the color and its reflection properties.

However, metallic paints (e and f) are somewhat different because of their unique glittering. This is because a dedicated

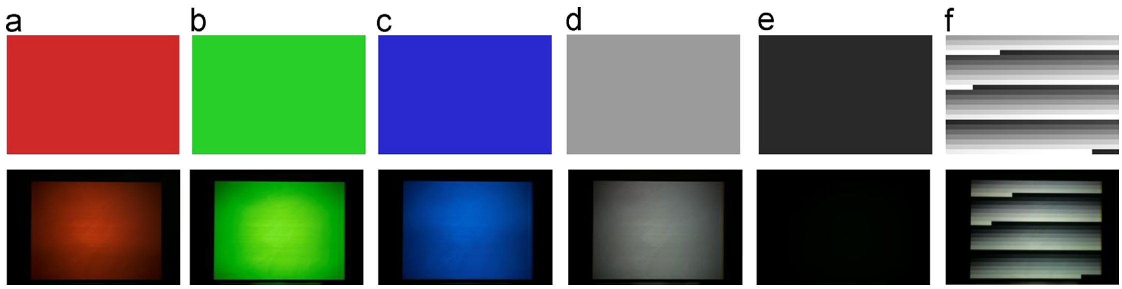

Fig. 8. The desired colors I (up) and the measured color C (bottom).

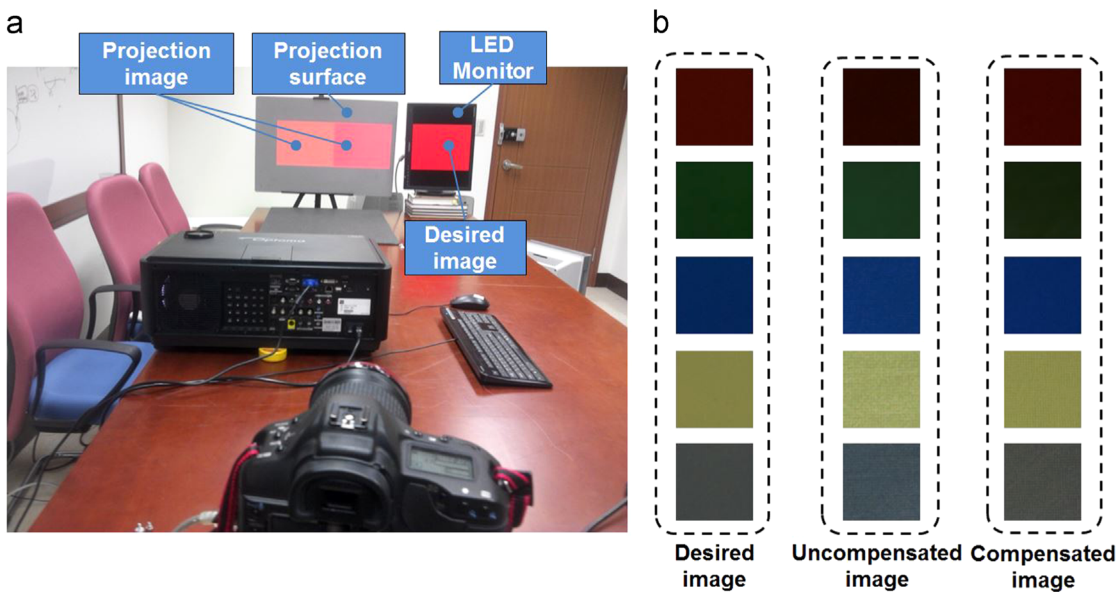

Fig. 9. (a) Projector-camera calibration system, (b) the desired image in an LED monitor (left), the uncompensated image (middle) and the compensated image (right) on the projection surface.

model for metallic paints was not applied in the BRDF modeling though metallic paints require an extremely complex model to realistically describe its reflectance properties. Moreover, the lighting condition and light characteristics of our rendering software is not exactly the same as the physical light source used in our experiment.

Table 2 lists the advantages and disadvantages of evaluations with the proposed appearance design technique and with the conventional design techniques, computer-aided color design [19] and computer-aided appearance design [6]. The proposed scheme provides a significantly improved intuitive and flexible environment in terms of design evaluation.

6. Case study: automobile design evaluation

Section 6 introduces a case in which the proposed SAR-based product appearance design methodology was used for appearance design of an automobile, and a design evaluation was conducted. In this study, our design process included mapping and verification of various materials for an automobile mock-up. Participants evaluated the design by interactively changing various colors and materials to be applied, and then the two best designs were selected. No digital displays for visualizing virtual contents are needed in the evaluation process.

Fig. 11 shows the process of making a mock-up of car that is used as the projection surface, which is about 6 cm in height and 18 cm in length. It was painted with a diffuse spray of gray color, and then the 3-D mesh model of a car was obtained using a structured-light scanner.

The materials we selected for our automobile appearance design were two each from solid and metallic paints. Using the pre-built material database, we obtained the results of applying various materials. Fig. 12 shows the rendering results of the four sample materials that were applied to the automobile mock-up. All results were rendered under a directional light, and the reason the rendering results are different from the material samples is that the light source is different from that used in the real world. To increase visual realism, an accurate modeling of ambient lighting is required; however, we did not take a complex lighting model into account because it is beyond the scope of our study.

Fig. 13 shows the results of projecting the rendering images in Fig. 12 onto a colorless automobile mock-up in order to

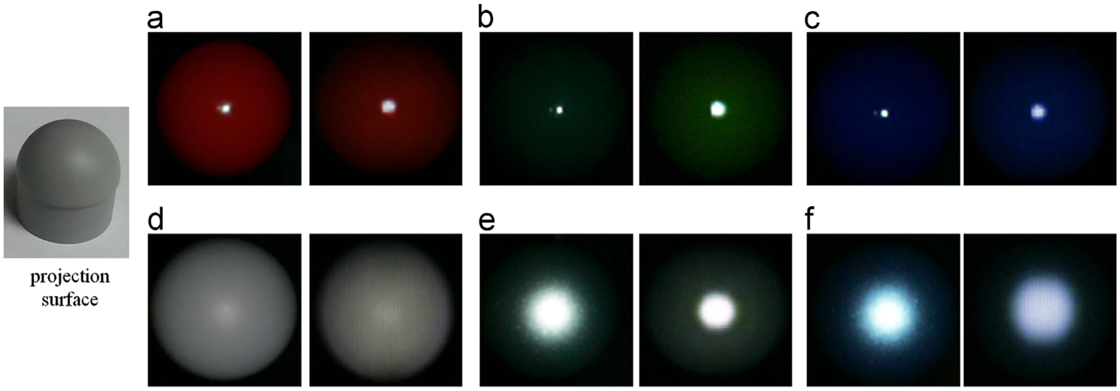

Fig. 10. Projection mapping results (right) for the different 6 physical material samples (left): (a) red solid paint, (b) green solid paint, (c) blue solid paint, (d) silver metallic paint, (e) green metallic paint, and (f) blue metallic paint.

Table 2
Comparison with existing computer-aided design evaluation methodology.

Techniques	Advantages	Disadvantages
Computer-aided color design [19]	Inexpensive; simple hardware components	Need for experienced designer Lack of consistent results
Computer-aided appearance design [6]	Efficient and accurate Ease of producing a product with pertinent material	Complex hardware setup High-quality monitor dependency
SAR-based computer-aided appearance design (proposed)	High sense of immersion for users/observers Possible 3-D display with a mock-up only	Complex hardware setup High dependency on projector's performance

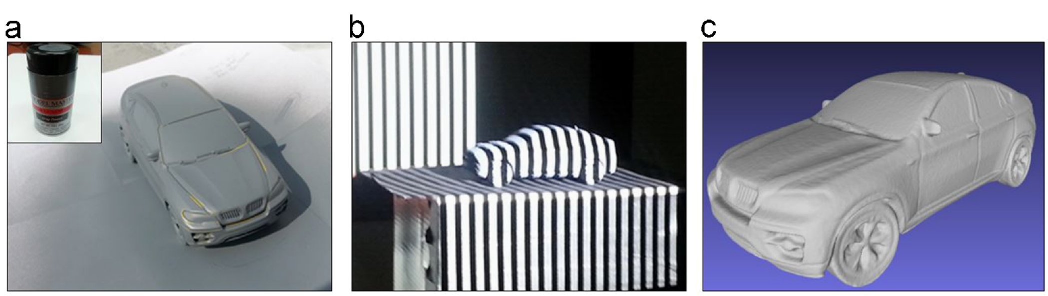

Fig. 11. A process of making a mock-up of car: (a) painting with a diffuse spray, (b) acquiring a 3D model using a structured-light 3D scanner, and (c) 3D mesh model of a car $|V| = 100k$).

evaluate the appearance design according to material. Because color correction of the projector-camera system was performed, the rendering results show almost no difference. Designers and users can compare between different appearances projected on site and select the best combination of color and material.

In comparison with Kim's method [19], in which multiple evaluators compare results from a single display and provide feedback, our proposed method allows a more intuitive and efficient environment for design evaluation because the different designs are augmented on an actual object, rather than a digital display.

Ten random people who are all male between ages of 24–33 are asked to evaluate the design and to select their best and second best design. As a result, Fig. 13(b) and (d) received the highest scores; see Table 3. From their evaluation and feedback, development of a new automobile could commence using the design of the pertinent color and material without recurring to trial and error cycles in the design process.

7. Conclusions and future study

In this study, we proposed an interactive design evaluation system; with this system, various colors and materials can be used for the appearance of a product, and the high-quality rendered images are projected onto a colorless mock-up of a product for designers and users to evaluate its appearance in an early design phase.

Fig. 12. The physical material samples and the rendering results of applying the corresponding materials.

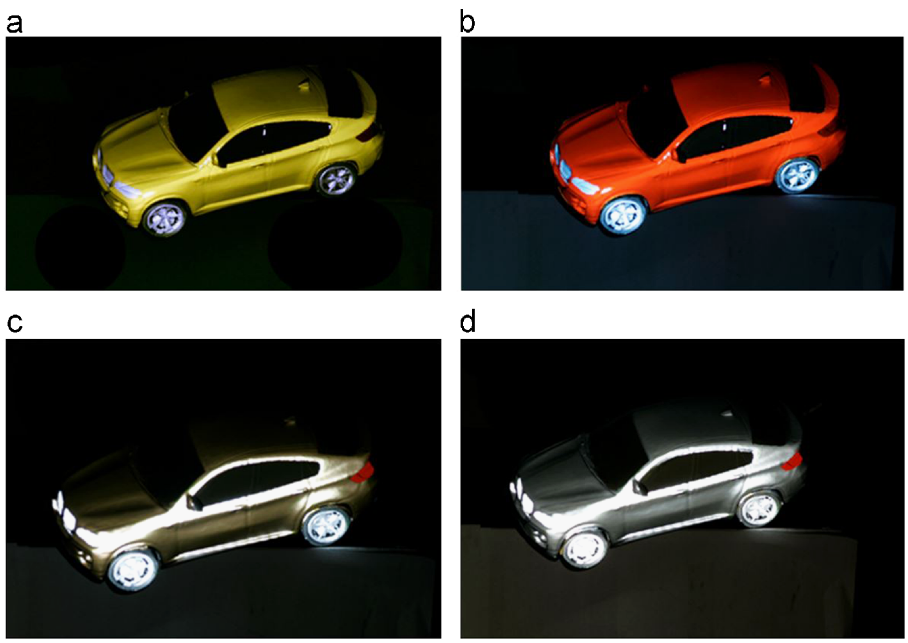

Fig. 13. The projection mapping results onto a mock-up of a car model.

Table 3
Design evaluation result.

	(a)	(b)	(c)	(d)
Best	1	6	1	2
Second best	0	3	2	5

Without a physical sample, this system allows designer intention and customer preferences to be reflected as early as possible, and thus both time and cost can be saved. In particular, the appearance of a product created with a computer can be projected on an actual model so that observers can experience real-life evaluation of the appearance design.

In the future, environmental lighting will be captured and our rendering will be executed based on this information to create more realistic scenes. We expect our future study to be actively used for purposes such as new product promotions.

Conflict of interest statement

We wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all of us.

We confirm that we have given due consideration to the protection of intellectual property associated with this work and that there are no impediments to publication, including the timing of publication, with respect to intellectual property. In so doing we confirm that we have followed the regulations of our institutions concerning intellectual property.

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