

Discussion on Digital Printing Reproduction Methods for Intangible Cultural Heritage Lacquer Art

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Abstract: The Lacquer art which has unique optical properties, multi-layered textures and rich colors is one of the most important type of traditional crafts. Because of the irreproducibility and long production cycle of hand-made lacquer application, it is hard to be disseminated or applied. We explore the technical routes by transforming the features of lacquer art into digital printing reproduction: Firstly, The optical properties (glossiness, transmission absorption characteristics), 3D data acquisition of surface texture of the lacquer surfaces are quantified; Establishing a mapping relationship from the lacquer color spectrum to CIELAB and spectral spaces. On the basis of above result, a spectral reflectance based method for color characterization modeling of lacquer was proposed that includes multi-channel separation techniques to solve the problem of metallic finishes and transparent layers simultaneously and prepress compensation algorithm for glossiness and surface undulations. For the printing process parameters, we explored different types of substrate surface treatments and primer layer simulation schemes, coordinated overprinting sequence and ink layer thickness, analyzing the enhancement mechanism of post-curing treatment on the lacquer film effect. All these digital methods can successfully reproduce the visual and tactile characteristics of lacquer, providing a quantitative technical route for the printing reproduction of traditional lacquer art.

Keywords: lacquer art; digital printing; spectral reflectance; multi-channel separation; surface texture compensation; process parameter adaptation

Introduction

The application of natural lacquer liquid through handbrushing is very valuable aesthetically and craft-wise regarding surface gloss, texture depth and color layers in traditional lacquer art. The inefficiency and inconsistency of manual production makes it hard to satisfy the demand of replication and dissemination for modern cultural products. Digital printing technology with high precision, repeatability and controllable processes could provide a new way to reproduce lacquer art. However if we apply the conventional printing processes directly, it won't be able to simulate the optical and tactile characteristics of lacquer surfaces because their reflection distribution, translucent layering effect and build-up lacquer textures doesn't have any digital description or printing compensation model. We need to develop a methodology covering all aspects from analyzing the visual features of lacquer art to adapting the printing process parameters. Our focus lies on quantifying the optical properties of lacquer surfaces, managing the color of the lacquer color spectrum, multi-channel separation strategy and pre- and post-processes' parameter compensation to bridge the technical link between the original object and the printed reproduction in this paper. With such a method constructed, we can improve the fidelity of traditional lacquer art on printing media giving us references to digitally reproduce other kinds of material-based crafts.

1. Digital Analysis of the Visual Characteristics of Lacquer Art

1.1 Quantitative Characterization of the Surface Optical Properties of Lacquer

The surface optical property of a lacquer coating is related to its molecular arrangement and refractive index distribution after curing. Different traditional lacquer art has chosen different brushing/application method which resulted in great difference in glossiness: for example, the polished

process will give a specular reflection effect while the brushed/wiped application gives diffuse reflection characteristic. We need to use the bidirectional reflectance distribution function to do angle-resolved measurement on the lacquer surface to get the intensity distribution of incident and reflected light over the hemispherical space. Using a multi-angle spectrophotometer we got the gloss value of lacquer sample with geometric condition (20° , 60° , 85°), or by using an integrating sphere to measure the total reflectance and the specular reflection component. Information then builds up into a numerical feature vector of lacquer surface gloss to match gloss in later printing reproduction^[1].

Another part of optical properties of lacquer surfaces: Transmission and absorption characteristics, Natural pigments and iron compounds in lacquer has a nonlinear reaction towards the absorption of visible light at different wavelengths. The transmission and absorption spectrum of lacquer films by UV-Vis-NIR spectrophotometer can reveal the physical mechanism behind its color formation. We need to measure its volume scattering coefficient and attenuation coefficient for translucent lacquer layer using Monte Carlo simulation to simulate the multiple scattering path of photons inside the lacquer film. Incorporate all these optical parameters into a surface property matrix will give us quantitative control reference for gloss and transparency to printing output devices without depending on subjectively comparing through eyes.

1.2 Three-Dimensional Data Acquisition of Lacquer Layer Thickness and Texture

Thickness distribution of the lacquer layer determines the visual depth and tactile sensation in lacquer artworks; thickness variation from traditional techniques like putty scraping and lacquer build-up vary from tens of micrometers up to several millimeters. Laser confocal scanning microscope or white light interferometer measures the lacquer surface non-contact with three dimensional point cloud data measured at submicron level vertically. We control environmental vibration and temperature drift while scanning to accurately register multi-frame data. A structured light three-dimensional scanning system project coded fringes analyze phase deformation to reconstruct the overall undulating morphology of the lacquer surface when it scans large area lacquerware. They fused together produce a lacquer layer thickness map which demarcate the geometric parameters of thick areas, thin areas and gradually transition zones.

Texture on the lacquer surfaces are caused by trace effect like brush marks, silk-screen impression and mottled pattern which can be regarded as a high-frequency spatial feature. We use a high-resolution digital microscope under oblique illumination capture an image sequence showing the microscopic morphology of the lacquer surface. Extracted the statistical properties (root-mean-square roughness, skewness, kurtosis, and autocorrelation length) of its texture; Investigated the orientation and periodicity of the texture using the discrete Fourier transform to get the energy distribution in the spatial frequency domain. Texture features could be encoded into several independent mode components by the principle component analysis. Using these 3D geometry data along with thickness information we encode them in a digital file which will go through printing processes to generate their corresponding physical height field or surface light-refracting structure.

1.3 Mapping of the Lacquer Color Spectrum in the Digital Color Space

Traditional lacquer color spectrum is associated with the source of natural raw material and refining process whose gamut ranges distribution around lightness and saturation are unequally distributed. By measuring the spectral reflectance curves of the lacquer color samples with different formulations using a spectrophotometer in the wavelength band ranging from 360 nm to 740 nm (each curve has reflectance value recorded every 10nm) we convert high dimension spectral data into CIELAB uniform color space by calculating its L,a,b coordinate of each color sample, delineate the convex hull boundary of the lacquer color spectrum on the chromaticity diagram. We demonstrate that typical gamuts of lacquer red, lacquer black, and lacquer yellow makes some cluster points on the a^*-b^* plane which differs from those of synthetic pigments. Establishing a lookup table based on spectra for lacquer colors avoid device dependent truncation error in RGB or CMYK spaces^[2].

In order to correctly map the lacquer color spectrum into the printing gamut, we require a gamut mapping algorithm: by doing spectral principal component analysis on the lacquer color samples, get the first three principal components as the spectral reconstruction basis vectors; at the output end, according to the spectral characteristics of the printing inks (CMYKOG six-color ink spectra) use the Jacobi iteration method for calculating spectral matching coefficient with the least squares sense; when the lacquer colors are outside the gamut of the printing device, take the strategy of combining clipping

and compression so that it is possible to adjust the saturation and lightness but not change the hue; finally do spectral verification such that the color difference ΔE_{00} between the sample and the target lacquer color is controlled within 1.5 which can be accepted in industrial printing. Finally set up a conversion model from the lacquer color spectrum to the digital encoding of printing channels.

2. Printing Color Management and Separation Methods for Lacquer Texture

2.1 Characterization Modeling of Lacquer Colors Based on Spectral Reflectance

The spectral reflectance curve of lacquer coating contains many absorption peaks and interference peaks especially for the visible light band. Spectroradiometer measures the reflectance value of different lacquer color swatches with wavelength range from 380 nm to 780 nm (sampling data every 5 nm), polynomial smoothing on all spectral curves to retain the characteristic absorption valley while removing high frequency noises. Cluster analysis is used to split the lacquer color spectrum into several spectral categories so that the root-mean-square error between the curves within each category should be less than 0.5%, establish the mapping function between spectral reflectance and chromaticity values through a radial basis function neural network fitting the nonlinear relationship; where the input is spectral band reflectance values, the output includes CIEXYZ tristimulus values, and the number of hidden layer nodes are chosen via cross-validation. Characterization model could accurately convert the measured spectra to a device independent color space which has an error level ΔE_{00} remaining under 1.0.

The high fidelity of our model depends on enough representative training samples. A total number of 120 lacquer color samples from different origin, refining temperature, and numbers of brushing application is selected to represent the typical lacquer color system (red, black, yellow, brown, and green) by averaging ten measurements per sample in standard D50 illuminant and 2° observer condition to remove random errors. By using principal component analysis we extracted the first six principal components of the spectral reflectance having cumulative variance contribution rate up to 99.2%, then we used leave-one-out cross-validation method to calculate the predicted color difference where the largest deviation happened at the deep black lacquer samples due to their low signal-to-noise ratio within the wavelength band. In order not to overfit, regularized term was added so that the spectral reconstruction error decreases even further. The characterized model can be easily embedded into the printing color workflow as a standard conversion module for the lacquer color input end^[3].

2.2 Multi-Channel Separation for Metallic Texture and Translucent Layers

Origin of metal texture in lacquer art is due to addition of metallic pigments (gold powder, silver powder, copper powder, or aluminum powder) according to their orientation and size distribution. We have to break out the limitation of four-color printing separation to reproduce metallic texture; so we use a multi-color separation with spot color channels like gold, silver, and pearlescent. Collecting multi-angle spectral data of metallic lacquer samples gets a parametric description about its angle-dependent color effect. Not only the spectral reflectance of the target lacquer color, but also spectral data of printing inks are inputted into an optimization engine which minimizes the spectral root-mean-square error as an objective function. Iterative reweighted least squares algorithm calculates the ink proportion of every channel through a spot color model without light scattering for the metallic channel. Distinguishing different hues must be done when reproducing golden lacquers such as blue gold and red gold: introduce spectral angle mapping as auxiliary constraints conditions.

The translucent layers are caused by the semi-transparent brushing property of lacquer that reveals the primer color under the upper lacquer films. We establish a multi-layer superposition model to compute the spectral transmittance and reflectance of all lacquer films according to the Kubelka-Munk theory in our separation process. In order to calculate the absorption coefficient K and the scattering coefficient S of the film we measure the reflectances of both thick and thin lacquer films and back-calculate them. The multi-layer superposition is calculated using the doubling method to obtain the total reflectance and transmittance layer by layer from bottom to top surface. Parameterize the transparent lacquer layers results convert to transparent ink channels in printing, allocate the ink quantity as per the superposition order during separation. Spatially varying transparency mask control the ink layer thickness of each channel if there exist gradually transparency regions. A separated file with CMYK and several spot color channels after multi-channel separation, each channel separately outputting their respective halftone dots.

2.3 Prepress Compensation Algorithms for Glossiness and Surface Undulation

The glossiness of the printed product is affected by both the surface property of the paper as well as the type of ink and curing method -- it usually differs from that of the high/low gloss of the original lacquer object. Firstly, we do a varnishing pretreatment on the printing substrate and measure their 20° gloss values when they are coated with transparent varnishes with different gloss level. A conversion function between the printed glossiness value and the target lacquer surface glossiness value which has a nonlinear S-shaped curve (large compensation slope at regions of low/high gloss) is established; we find out the coating parameters and drying condition needed for the varnish according to the target glossiness. If the glossiness difference is greater than 15 GU, then we use a regional spot varnishing strategy based on the nozzle array of the digital varnishing device to control the amount of varnish deposited in different areas [4].

Surface undulation refers to the physical height change on the surface of a printed product with raised effect by screen printing or digital foil stamping process simulating the build-up texture of lacquer layers. Prepress compensation algorithm should generate a proper printing undulation control file based on the lacquer layer height field data obtained through three-dimensional scanning. Height field will be discretized using a grid matched with printing resolution; then convert the height value for every grid cell into screen tension parameter in screen printing or hot-pressing depth parameter in digital foil stamping. We need consider the height gradient between two adjacent grid cells when doing the compensation so as to avoid any unnatural steep step. For those parts exceeding 200 micrometers in height, we take a multi-layer build-up strategy: one layer drying before another layer is superimposed. Output result is a height mapping table guiding the printing device apply a corresponding thickness of transparent primer paste or foil stamping foil at certain position. After curing, use a laser rangefinder to check the conformity between the real undulation and the target height (error less than ± 10 micrometers).

3. Adaptation of Printing Process Parameters for Lacquer Reproduction

3.1 Substrate Surface Treatment and Primer Layer Simulation

The surface energy, roughness and porosity affect the adhesion/spreading properties of printing inks. To simulate the lacquer primer coating by physical/chemical modification on the substrates (paper, plastics, composite) (corona discharge or plasma treatment increases the surface polarity such as the water contact angle below 30 degrees), we use a primer coating with micron-sized inorganic fillers giving a controlled micro-rough structure whose Ra value varies between 1.5 μm and 3.0 μm for substrates which do not have enough roughness; this provides better mechanical anchoring force of the subsequent transparent primer paste. The surface free energy including both dispersive and polar parts are measured before and after treatment to ensure interfacial compatibility with the target lacquer layer[5].

In order to simulate the primer layer, we have to fabricate a base medium which has similar optical and mechanical properties before printing. Select a transparent high, low viscosity UV-curable resin as the primer paste materials, adding silica or calcium carbonate into the system so that the rheology achieve a thixotropic index between 4-6. Apply uniform primer paste on the treated substrate surface by screen printing or slot-die coating method with a wet film thickness from 30 μm to 50 μm . The surface glossiness and pencil hardness are tested after curing: glossiness need to be within the matte range (20 GU to 40 GU) and hardness reach HB grade. Compare with the data of the lacquer primer coating, adjusting the ratio of monomer to photoinitiator in the resin formula so that the curing shrinkage rate is less than 5% and obtain an optical reference surface for further overprinting of color inks.

3.2 Coordinated Control of Overprinting Sequence and Ink Layer Thickness

The overprinting sequence determines how many lights pass through each ink layer until reaching the bottom layer. The overprinting rules used during our printing process are as follows: light to dark colors and transparent to opaque colors. Firstly we print transparent channels covering effects layers like gold powder and pearlescent followed by spot colors and four-color inks one after another. Semi-curing treatment for every color group is carried out using ultraviolet lamps under the control of curing energy (40% to 60%), compared to the original standard value while leaving some active

functional groups so that improving interlayer adhesion. Verification on the overprinting sequence is measured by the color difference value before and after printing of each layer via a spectrophotometer, if the actual color difference of any layer varies from its theoretical value by more than $\Delta E_{00} = 2.0$, the order of this layer will be changed accordingly.

Matching Ink layer thickness with order of overprint, avoid dot gain/setoff on the backside because of too much local ink volume. Closed loop control model based on the ink transfer characteristics: The thickness distribution map of the target lacquer sample (input), Ideal ink volume for every printing unit (output). Metallic ink channel thickness is controlled between $8\ \mu\text{m} - 12\ \mu\text{m}$ to guarantee the orientation of metallic pigments. Translucent/transparent channel thickness ranges from $4\ \mu\text{m} - 6\ \mu\text{m}$ depends on the line count and ink carrying capacity of the anilox roller. A density compensation algorithm for overlapped areas which adjusts the ink volume of the next printed ink by the coverage of previous printed ink. Online thickness gauge measures the wet film thickness after each color group giving feedback to adjust the adjustment unit of the ink fountain key opening. Coordinated control makes sure the overall thickness deviation of the whole overprinted layer do not exceeds $\pm 1.5\ \mu\text{m}$.

3.3 Enhancement Mechanism of Post-Curing Treatment on the Lacquer Film Effect

Curing and post-treatments after printing are also critical for determining the final texture of the simulated lacquer film. In the UV curing process, the photoinitiator absorbed the radiant energy and decomposed into free radicals that initiated the crosslinking polymerization of monomers/oligomers. Mercury lamp (broad spectrum) or LED light source (narrow band and low heat accumulation advantage) will be chosen based on the ink systems. Curing energy density varies between $200\ \text{mJ}/\text{cm}^2$ to $400\ \text{mJ}/\text{cm}^2$ with a two-step cure: first step is rapid curing to avoid tackiness at the surface level while second one is deep-level curing to improve cohesion strength. Degree of curing was measured through Fourier-transform infrared spectroscopy to determine the double bond conversion rate, then further treatments can take place if the conversion rate reaches above 85%^[6].

The three methods used in post curing treatment are: physical polishing, chemical polishing and secondary recoating. The physical polishing uses 4000-mesh to 7000-mesh micron-grade sandpaper with slight abrasion to eliminate the surface orange peel and bubble defect which decrease the surface roughness down to R_a less than $0.1\ \mu\text{m}$; Chemical polishing uses ethanol or ethyl acetate vapor fumigation to dissolve and level up the surface so as to increase glossiness from 10 to 15 GU; Secondary recoating means printing one more very thin (within $2\ \mu\text{m}$) high transparency resin layer on top of the polished layer to form a mirror effect like polished lacquer. Afterward we can perform thermal aging test by placing it into a constant temperature oven at $60\ ^\circ\text{C}$ for 48 hours to watch the change of glossiness and color. We believe this post treatment could stably simulate the surface property of the original lacquer object when the color difference ΔE_{00} is less than 1.2 and the glossiness attenuation is lower than 5 GU.

Conclusion

In this paper we propose a three-tiered technical approach towards digital printing reproduction of lacquer art: visual feature analysis, color management and separation, process parameter adaptation. Quantification of surface optical properties and three-dimensional data development a computational model for lacquer surface gloss, texture and color; Characterization modeling from spectral reflectance and multi-channel separation solve the challenge of metallic texture and translucent layers in printing. Through substrate modification, primer layer simulation, coordination of overprinting and ink layers, and post-curing treatment achieve a near-reproduction of the physical texture of lacquer films on printed products. Higher resolution dynamic spectral acquisition research and real-time feedback printing system can further improve the compensation accuracy of surface undulation at sub-micron level. Using different curing light sources and nanomaterials in lacquer film simulation will be explored to improve the abrasion resistance and aging resistance of printed products. For reproducing multi-material composite lacquerware (such as those inlaid with mother-of-pearl or eggshell) there's need to develop hybrid optical and mechanical models of heterogeneous materials.

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