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FINAL REPORT ON THE PROJECT: OPTICAL INTERACTION BETWEEN INK AND PAPER

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1. BACKGROUND - COLOUR PRINTING WITH DIGITAL PRINTS CONTINUE TO GROW

The evolution of digital print continues. There is a transition from black & white print to four colour printing on large xerographical print units. Small very cheap desktop laser printers dominate the small office sector and have also started to penetrate the home market. The digital photography explosion means that very high quality photo inkjet prints can now be printed at home. The inkjet printer units are often multipurpose, meaning that features like scanning, copying and printing can be accomplished with a single unit. The inkjet printers also have plain paper printing options, which means that home & small office today have versaite colour printing facilities. The small inkjet printers are getting more sophisticated with smaller droplets, more nozzles and wider print heads. HP has launched their first printer heads with Edgeline technology, meaning that the print heads are as wide as the paper and are therefore static, entailing a vast potential increase of speed and accuracy. Other inkjet devices focus on extreme print quality with up to 12 process inks in order to obtain high colour gamut and smooth tone steps.

Traditional print processes like offset use cyan, magenta, yellow and black as process colours, and standardized methods are established to control the process and evaluate the influence of the substrate. The colour reproduction is often made with well known halftoning algorithms where the ink level is constant for each ink dot and the tones are rendered by varying the size of the dots. Besides new algorithms and more than four process inks, the colour reproduction of digital print is a combination of varying the ink level in each dot and varying the dot size. Small desktop units, laser and inkjet, thus have a range of different settings.

The complex colour reproduction of digital printing units calls for new general evaluation methods that the paper industry can use when developing new paper products for these printing units.

As colour printing finds new markets, the demands of correct colour is increasing. Within traditional print, colour management is now established and efforts are made within international standardization organizations to further develop colour management to achieve consistent colours. Colour management is also interesting for the home and office market and Microsoft will put a lot effort to develop easy to use colour management tools in their new operating system Vista. The challenge is to get consistent colour from a digital camera, view it and maybe adjust this colour on the computer screen and get the same colour on print. A crucial parameter in colour management is the colour gamut. The colour gamut of the source, e.g. a digital camera or a scanner, is different in size and shape from the output colour gamut, e.g. a printer, and adjustment must be done. The colour gamut for printing devices needs thus be determined in all colour management process were print is involved. The colour gamut of a printer is the result of the optical interaction between ink and paper.

The aforementioned evolution implies that the simulations and measurements dealing with the optical interactions between ink and paper are more relevant than ever. It is a challenge for the paper industry to find evaluation methods for colour reproduction that make it possible to study the influence of the substrate. Simulations and general methods like colour gamut determination have turned out to be a very good approach in order to understand the interaction between ink and substrate.
2. THE GOAL OF THE PROJECT

The goal of this project was to improve colour in digital and traditional print. This should be accomplished by creating computer based simulation tools for the interaction between ink and paper. In the first phase a simple version of such a tool was completed. This software could simulate inks that are completely mixed and penetrated into the paper. In the new software, it should also be possible to simulate printing methods like offset, where the inks do not mix but instead are applied in layers. The aim was also to be able to add more than four process inks. The software should be in modular form which also means that a range of fundamental optical equations and transformations between different colour systems will be collected as Matlab routines that could be used independently. Efforts should also be made to verify the simulations by extensive printing with test charts that reflect the simulations.

3 ACTIVITIES AND OBTAINED RESULTS

3.1 General

The new software is much faster and has enhanced possibilities compared to the first version. Besides mixing the colour, it is now possible to simulate the effect of printing the inks in layers on top of each other. Simulations show how printing dot-on-dot gives lower lightness of the print compared with dot-off-dot, i.e. were the dots are placed next to each other. The first simulations with more than four process inks show that a lot of new knowledge also can be obtained in these fields. A significant improvement is that the software now can be compiled executed standalone, i.e. it can be run without a Matlab licence. This makes it much easier to disseminate the tool to all interested parties. The software is in modular form, meaning that a range of fundamental optical equations and transformations between colour systems can be accessed as a Matlab toolbox.

A laboratory study in cooperation with LiU and supported by T2F has given increased insight of the effect of ink penetration of ink into the substrate and the negative influence of high light scattering of the substrate. Weak colour strength due to non-ideal behaviour of ink were also observed in this work and this phenomena has been studied in several investigations. The reasons for the weak colour strength in digital print was clarified by simulations. Colour rendering with continuous tone and different ink weight were compared with colour rendering with different surface coverage. Printing with small and large dots also gave insight of the importance of the non-ideal behaviour of process inks. In another investigation, simulation with different degree of ideal and non ideal properties of the ink showed that the light absorption of the process inks should overlap each other in order to obtain the largest colour gamut.

The colour gamut was studied by creating digital test charts that define the outer shell of the gamut. By also including digital test charts of the inner parts of the colour gamut, it was possible to explain many of the colour transformation and calculations that are involved in colour management. This investigation was possible to perform using a range of tools of the “Optical properties toolbox”.

3.2 New knowledge from new software

In the project two new software programs have been developed. Much of the research and knowledge won in the project have been included in the software. Therefore we have chosen to describe them more in detail in this section.
3.2.1 InkCognito software

**InkCognito** is a MATLAB package for calculating reflectances of prints using Kubelka-Munk equations. It can be used for simulating inkjet printing as well as offset printing. In **InkCognito**, inkjet printing is assumed to have the inks penetrating the substrate, whereas for offset printing, the inks are assumed to be layered on top of each other, without penetration. Two different halftoning strategies can be used, dot-on-dot and dot-off-dot or any combination thereof in a continuous scale.

With some restrictions, specifically dot-off-dot printing, **InkCognito** can be used with any number of inks. It is quite feasible to simulate a future printer having so-called spectral inks.

**InkCognito** can calculate the reflectances for any combination of inks. It can however not be used to meaningfully visualize prints having inks that are used conditionally, depending on the lightness of a wanted color. This means that not even ordinary CMYK printers can be visualized.

The main use of the package is however not to precisely calculate the reflectances, but more to be used a learning tool. The program makes heavy use of Matlab 3D graphics and every change in the parameters is instantly visualized. This makes the package ideal for “what-if” tests that can inspire to new ideas and further investigations.

Results can be saved as a Matlab data file or exported to Excel. It is also possible to enter spectral data for media and inks in Matlab or Excel and import it to **InkCognito** for testing.

It is possible to import measured color gamuts into **InkCognito** and compare these gamuts with other imported or simulated gamuts.

**InkCognito** can also make live animations of the effect of parameter changes, which can be saved in several file formats, for easy inclusion in e.g. a PowerPoint presentation.

3.2.2. OptProp software

**OptProp** is a MATLAB toolbox used for calculation and examination of optical properties. It is not optimized for large data sets, i.e. it is not a god idea to operate on large images. Instead, it is meant for rather small data sets, less than 10000 samples.

The main feature of OptProp is that it keeps the dimensionality of all matrices during calculation. It is quite feasible to analyze multidimensional data, such as test charts for a number of printers in one go. Other toolboxes, such as MATLAB’s own Image Processing Toolbox, forces the user to handle this multidimensionality.

The routines in OptProp have been carefully designed to be an integrated toolbox, so that the output from one routine seamlessly can be used as input to another routine.
3.3. Investigations summarized in reports dealing with optical interaction between ink and paper.

The effect of ink penetration and light scattering of substrate on colours of inkjet has been simulated and reported in phase 1. An investigation where hand sheets were created with hydrophobic agent and filler gave results that agreed with the simulations. The problem with non ideal behaviour properties of inks were demonstrated were maximal colour gamut was achieved for less colour amount than normally is used for an HP inkjet device. (1).

Colour reproduction of digital print is often made as a combination of surface coverage of the substrate with ink, halftone, and multi ink level technique, continuous tone. These two colour reproduction methods have been simulated using software created by M-Real, see below. The simulations were compared with offset and ink jet prints. The results showed that offset had a halftone character whereas inkjet more resembled continuous tone colour rendering. Print with an HP printer where it was possible to control the dot size was also included in this investigation. The size of the dots and non ideal behaviour of process inks can also explain the colour properties of inkjet and offset prints (2).

Printing with test charts that define the colour gamut have been performed in co-operation with the industry partners. One of these series have been summarised in a report. The analyses clarified that the offset ink that gave high colour gamut had magenta with less non-ideal behaviour compared with magenta of the reference ink. The low colour gamut of offset prints on uncoated paper resembled inkjet prints on plain paper. Xerographical prints gave high and equal colour gamut of uncoated and coated paper (3).

In colour management, the different colour gamuts of the source and the printer are taken into account. The special feature of small desktop printers facilitates the study of the workflow of colour management. Both the test image used for colour management and the input to the printer are in RGB format. This opens up the possibility to directly compare the colour corrected images to the non-corrected. The properties of colour corrected printers were reviewed by creating digital test images defining the outer hull of RGB colour space and trace how these test images were processed in the colour management workflow. It was clarified that non-colour corrected images often have very bad print quality due to colour failure. Traditional print evaluation can however not be performed for colour corrected printers. New print quality routines are needed. (4)

3.4. Further development of the new model DORT2002

The radiative transfer based model DORT2002, which is adapted to simulation of light scattering in paper and prints, has been created outside of this project. However, a further development has been done in some parts. The possibility to use DORT2002 from inside Excel, including a graphical interface, has been developed. The possibility to simulate – in detail – a spectrophotometer with D/0 geometry has been developed, and this feature was used in a master’s thesis mentioned above. This will in the future be complemented with other instrument geometries, and this will be a powerful tool in several analyses. The possibility to handle discontinuous changes in refractive index has been developed. This will be tested against the approximation featured by the combination of Kubelka-Munk and the Saunderson correction. Finally, parameter estimation methods have been developed, which is the final crucial step towards a next generation Kubelka-Munk, with higher accuracy, a wider range of applicability, and for increased understanding. DORT2002 is now fully equipped to be used extensively in future detailed and quantitative studies.
3.5. Thesis works

Two thesis works have been completed within the project. Both thesis works were dealing with the weakness of the Kuebelka Munk theory that has been used in Phase1 and Phase 2 (this project). The thesis works have been paid by M-real. In the thesis work “Light scattering/reflection from surfaces the Saunderson correction”, the theoretical background of this seldom used correction was reviewed. The theory was adapted to a D/0° instrument and a first trial to use this correction was performed. This approach will be studied further in coming activities, phase 3. The thesis work “deals with the anisotropic behaviour that all materials have as long as any kind of light absorption is involved. The causes of anisotropic reflectance are investigated and it is shown, using analytical methods and Monte Carlo simulations, that it is caused by the relative contribution from near-surface bulk scattering. This means that the anisotropy increases a) for highly absorbing materials (since light penetrating deeper is absorbed to higher extent), b) for optically this materials (since light penetrating deeper is transmitted to higher extent) and c) for oblique incidence illumination (since a certain optical path length reaches a shallower depth). The work also used the new model DORT2002 extensively for quantitative simulations.

4. ACTIVITIES MADE BY THE INDUSTRIAL PARTNERS

This project is characterised by a very close cooperation between industry and university. Approximately 50 percent of the research has been produced within companies and 50 percent in university, in that sense the project is an example of co-production. The active research partners in the project have been Mid Sweden University, M-real co-operation, MoRe Research and Linköping University.

Besides active discussions in project meetings, the other industrial partners have taken part in the project by performing test printings and creation of own software that has been utilised in the project.

M-real has in cooperation with DPC created a range of test charts defining the outer shell and inner parts of the colour gamut. M-real also created routines to measure these test charts with a spectrophotometer (Spectrolino) and made a special evaluation software that DPC has bought from M-real. M-real has also made a software in Excel where the fundamental simulations of the optical interaction between ink and paper were included. The output of the simulation was performed so that it was compatible with the evaluation of the printed test charts. With this approach it has been possible to directly compare properties of the printed colour gamut with properties of the corresponding simulated gamut. M-real have also been following this project by establishing internal paper development projects taking care of the results produced in the open project.

Test charts that define the outer hull of the colour gamut were created in such a way that it could directly be printed with a full scale offset or flexo printer. Stora Enso made an extensive test printing with four different paper grades using traditional ink and also an ink that were supposed to give higher colour gamut. M-real made test printing in inkjet with photo inkjet and plain paper inkjet and also laser print on plain paper and coated paper. This print tests were summarized in a report (2). Öhlunds Tryckeri AB made test printing on coated papers with different ink amounts. SCA made full-scale printing in Flexo together with STFI-Packforsk.

Some of these results were also presented at an international workshop, “Paper and Colour - Future Measurement and Standardization”. The workshop was attended by major companies from the inking
industry, the paper industry and the graphical industry. The ideas behind the workshop emanated from findings made in this project. In that workshop, large interest was shown in the new model DORT2002, where radiative theory has been adapted to paper optics. Within colour management especially on the business side, there is now a discussion on how future optical measurements should be made to fulfil the requests from both the paper industry and the graphical industry.

This problem has also been dealt with in our investigation since both the type of instrument used in the paper industry and the ones in the graphical industry have been involved in our measurements. A first trial to get a deeper understanding of the differences between these instruments was accomplished in a thesis work. It was shown that differences in calibrations, the size of the measuring and illumination spot and differences in the treatment of the spectral values were three causes for differences between the instruments. The fundamental difference in optical geometry of the instrument used in the paper and graphical industries were however not studied in that investigation.

The workshop will lead to a common EU 7th framework application where participation from 10 different companies and several European universities already are committed to the application. The result of the workshop has also been presented to two working groups within the ISO standardization structure.

5. COOPERATION WITH OTHER RESEARCH GROUPS

The paper optics research group within STFI-Packforsk has been actively following the work, a common PhD project will be started as a result of the work. Researchers at Linköping University and Karlstad University has been directly involved in carrying out research within this project.

6. INFORMATION AND COMMUNICATION

The results have been presented and discussed with industrial partners in ordinary project meetings that were held twice a year. Seminars have been held at SCA and Mid Sweden University in Sundsvall, LiU in Norrköping, and at numerous occasions at DPC in Örnsköldsvik. The results have also been presented at a number of internal seminars and information meetings within M-real. At the last project meeting, colleagues from universities and the involved industry partners were invited to a one day seminar, where some of the results were presented. About 25 people attended this seminar. A follow-up meeting to present the project result to the paper industry in Finland is planned for January. Research result and information of the project have also been presented at the DPC website as well as within the FSCN and T2F framework.

7. REPORTS RELATED TO THE OPTICAL INTERACTION BETWEEN INK AND PAPER

1. Ink penetration of inkjet; a handsheet study
2. Colour reproduction of offset and inkjet, half tone and continuous tone
3. Colour gamut of offset, inkjet and xerographical prints
4. ICC profiles for RGB printers
8. SOME OF THE SOFTWARE

1. Print Sim for Matlab
2. InkCognito the compiled new software
3. Toolbox OptProp
4. A "Light" PrintSim for Excell
5. Evaluation of colour reproduction

9. RADIATIVE TRANSFER PUBLICATIONS