Rendering complex colour inside 3D printed foods

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Abstract

Three-dimensional (3D) printing refers to a group of digitally controlled, additive manufacturing technologies increasingly used to fabricate customised objects from a range of possible materials, including food ingredients, using a digital image file representing the object. A novel variation on 3D *food* printing is being developed to customise the appearance of foods with an embedded 3D colour image by the selective blending of primary colorants. This capability is beyond what is needed usually for the coloration of bulk, single food matrices.

In this thesis, non-food techniques of colorimetric matching (used in computer match prediction) and colour gamut mapping (from cross-media colour reproduction), were investigated as potential methods for dye recipe computation by the new 3D colour food printer. The aim was to develop a model for transforming image RGB data to dye recipe data, taking into account the variable effects of food properties. The two techniques were applied to the problem of matching a set of standard tile colours using a set of primary colorants in model food substrates. Kubelka-Munk (K-M) blending equations underlying both techniques were developed for blends of Brilliant Blue, Ponceau 4R (red) and Tartrazine (yellow) food dyes when added to a microwave-baked cake and to four variants of a wheat starch gel. Validation of the model for the cake blends was shown the by $\Delta E^*_{ab,10}$ differences between computed and measured $L^*_{10}a^*_{10}b^*_{10}$ colours falling within range of a visually acceptable match (three $\Delta E^*_{ab,10}$ units). For some of the gel blends, the $\Delta E^*_{ab,10}$ differences reached five units.

Dye recipes computed by a modified colorimetric matching algorithm to match target tile colours with cake colours at times called for negative quantities, or totals that exceeded the legal limits for foods containing dyes, indicating that the target colour was outside the range (gamut) of the cake-dye system. In these recipes, individual negative dye quantities were increased to zero, and totals scaled back to within the legal limit, retaining relative dye proportions. This resulted in close differences between tile and cake before scaling (with computed $\Delta E^*_{ab,10}$ values of less than three units for as many as eight of the twelve target colours) becoming much larger

after scaling (up to 39 $\Delta E^*_{ab,10}$ units), though visual inspection of the colour pairs suggested that the matches might be closer.

The gamut of perceived colours from a coloured food is not only constrained by legal restrictions on dye addition, but dependent on the properties of the food itself, such as its background colour (seldom white) and the light-scattering effects of surface texture. Compared with colour images, foods are likely to have a more limited colour gamut, the size of which is expected to vary with changes in formulation and processing. Gamut mapping techniques were used to investigate the extent to which the target tile colours themselves needed to be scaled back before matching solutions and corresponding dye recipes could be computed. Using four samples of the gel that differed only in their level of (artificial) browning, including white, the impact of browning on the colour gamut was determined. Using the cake, solutions from gamut mapping were compared with those from colorimetric matching.

A gamut of discrete colours is treated as a continuous volume in colour space. In the absence of a published gamut calculation for coloured foods, a technique was developed to compute a mesh of points on the colour gamut boundary. Boundary colours were computed using dye blends not exceeding the legal limit, and spaced such that $\Delta E^*_{ab,10}$ did not exceed three units. This method was applied to the white (non-textured) gel containing dye blends, to generate a 'base' gamut. The absorption behaviour of each dye was found to be largely consistent among the white and browned gels which enabled quick computation of colour gamuts for the brown gels by substituting the absorption spectrum of a brown gel for that of the white in the K-M equation. The colour gamut was found to decrease in size and to shift position with increased gel browning. The dye blends that were used to compute the colour gamut boundary for the whitened gel were combined with the absorption spectrum for the cake to compute the gamut boundary for the cake colours. All colour gamuts were specific to the standard D65 illuminant and 10 degree standard observer.

In the investigation of the effects of browning, colour gamut mapping began with the initial replacement of each tile colour with a colour from the white gel gamut. All colours were replaced gradually by a darker, and often less chromatic, colour, as the level of browning in the gel was increased. As a result of the reduction in gamut size with increased gel browning, the difference between tile colours and their replacement targets in each of the reduced gamuts was smaller for tile colours having ‘brown’ characteristics (such as Orange, Red and Yellow) than they were for blue-, pink- and green- coloured tiles. Larger increases in total dye quantity with increased gel browning were needed for the latter group of colours than for the former. For most colours an increase in the relative proportion of the darkest dye in the recipe was also needed. The actual dye quantities computed for each replacement colour depended on the availability of mesh points in the region of colour space in which the tile was located.

Colour gamut mapping required a heavier computational load than the colorimetric matching technique to provide solutions for tile colours in the cake-dye gamut. Although not always giving solutions in the same angular region of colour space as the tile colours, colorimetric matching was able to produce similar $\Delta E^*_{ab,10}$ differences between tile colour and best cake match as did colour gamut mapping, for not necessarily more or less total dye.

Two forms of a generalised algorithm are proposed for the computation of dye recipes by the 3D colour food printer. One algorithm is modelled on a workflow for cross-media colour reproduction. A series of transformations that account progressively for the effect of individual characteristics of the food printing substrate on the achievable gamut from dye blends is incorporated into the main series of transformations that transcribes RGB image data to dye recipe data. In the other algorithm, modelled on colorimetric matching, it is the progressive effect of each individual characteristic on the light-absorption characteristics of the un-dyed food printing substrate that is accounted for, and incorporated into the main matching workflow.

Preface

This thesis is written in the style of (but not formally complying with) a submission based on publications, as described in the Handbook for Doctoral Study, Doctoral Research Committee, Massey University, Version 7, January 2011; each chapter following the Literature Review and preceding the final Overall Discussion is formatted as an extended research paper. Within research Chapters Four, Five and Six, the methods and results are described and discussed for each stage of the work, rather than in separate Methods and Results sections for the entire body of work. All research chapters (Chapters Four to Seven) have their own Introduction and General Discussion sections. Appendices follow each of these chapters. Due to the format of the thesis some of the detail that is covered in the Literature Review is repeated in the remaining chapters, which are presented in chronological order.

A shorter form of Chapter Four was published as an original research paper in the Journal of Food Science (Kim *et al.*, 2012). A copy is not included here. It is intended to use other chapters as the basis for future manuscripts.

Unless stated otherwise, the figures in this thesis are the work of the author.

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