A Colour Engineering Toolbox

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Abstract

A toolbox of Matlab functions has been made available for readers of *Colour Engineering* (Green and MacDonald, 2003). Functions are included for the computation of colorimetric quantities, colour difference, characterization and psychophysics.

Introduction

Colour Engineering was published by Wiley in 2002, and was reprinted in 2003. All royalties are dedicated to a student award administered by the Colour Group (Great Britain).

Although end-user applications for colour imaging are commonly coded in C++, Matlab has many advantages for education, research and development, particularly since it allows focus on the development of algorithms without the overhead of writing Windows applications.

Version 1.0 of the Colour Engineering Toolbox has been made available to support readers of the book and students of colour imaging. The Toolbox contains a range of functions which implement algorithms described in the book (particularly chapters 3, 6 and 10), as well as additional and updated functions for colour appearance and psychophysics, and some utility functions to increase computational efficiency and reduce the user load.

The functions have been written with two main aims in mind: to make clear how the underlying algorithm is implemented, and to achieve a reasonable efficiency in computation. The functions are fully vectorised to make use of Matlab's array processing, and will process many thousands of pixels per second (the exact number depending on factors such as the host processor, hard disk speed and available memory).

Functions have been tested on a minimum of 1.0E6 data points, often many more. For functions that are the inverse of other functions in the toolbox (e.g. xyz2lab.m and lab2xyz.m) accuracy is limited by the finite precision of floating point calculation and the invertibility of the algorithms. Typically several thousand iterations are required to accumulate an error above 1.0 ΔE^*_{ab}, and where available published data has been used to test the accuracy.

Where possible, algorithms are based on methods recommended by competent bodies such as ISO and CIE. Graphic arts parameters are used as defaults for many functions, including those specified in ISO 13655 (ISO, 1996) and ISO 3664 (ISO, 2000)

A summary of the functions in the toolbox is given below, and further details are provided in the help section in each function. For more information on the algorithms used, please see the references given.

Colorimetry

Computation of colorimetric quantities begin with conversion of spectral data to tristimulus XYZ. The Toolbox function r2xyzd50.m uses the weights and computation procedures specified by CIE Publication 15.2 (CIE, 1986) and ISO 13655 (ISO, 1996), including the D50 illuminant and CIE 1931 Standard Colorimetric Observer.

Other colour spaces supported in the Toolbox include CIELAB, u',v', colorimetric density, and sRGB (IEC, 1999).

CIELAB data is always represented relative to some reference white. In colour engineering, this is commonly either a perfect diffuser, or the white point of a device or medium. If the XYZ tristimulus values were originally calculated for a particular illuminant, it is possible to compute media-relative coordinates using the abs2rel.m function if the tristimulus values of the media under the same illuminant are known; equally it is possible to return to values relative to a perfect diffuser using the rel2abs.m function.

Recent work on colour appearance has culminated in the publication of the CIE CAM02 colour appearance model (Moroney and others, 2002). The function XYZ2CAM02.m computes CIECAM correlates J, C, h, Q, M, ac, bc and s, while JCh2XYZ inverts the calculation to yield X, Y, Z from J, C, h.

Polar calculations

Cartesian CIELAB coordinates can be represented as perceptual correlates lightness, chroma and hue by conversion to polar coordinates.

As described in *Colour Engineering*, the atan2 function returns the two-quadrant solution in radians. Although trivial, further steps are required to compute the four-quadrant solution in degrees. Care also needs to be taken when adding and subtracting hue angles, since if the angles lie either side of 0 degrees an error can arise. The hue_angle, angle_add.m and angle_diff.m functions correctly perform these calculations.

Colour difference

As well as 1976 CIE UCS colour difference, *Colour Engineering* describes a number of advanced colour difference equations. These include CMC, CIE94 and CIEDE2000, all of which are supported in the Toolbox.

Characterization

A range of different techniques for characterizing colour devices and media are described in *Colour Engineering*. Two fundamental techniques are polynomial regression and colour look-up tables.

Polynomial regression is used to find the set of coefficients which describe the relationship between two sets of data, minimising the least-squares error between the two sets of data. Full details are given in the chapter 'Overview of Characterization Methods'. The function charac3.m is used to compute the coefficients, while polyconvert.m will convert between two colour spaces using these coefficients.

Three-dimensional table look-up is the basis for colour conversion as encoded in most ICC profiles. At run time, the transformation engine extracts the stored values closest to the target colour and performs 3D interpolation to compute the output value. The number of surrounding colours used can be between four and eight.

3D table look-up and interpolation is supported in MatLab, using the interp3 function. However, this function requires that the table data is first gridded, while the method of encoding used in ICC profiles (Wallner, 2002) stores each node just once in a mxn structure, where m is the number of nodes in the table and n is the number of colours.

The function lookup3d.m performs table look-up directly on ICC-style encoded tables.

It first calls extract3d.m to locate the bounding cube around the point of interest; this uses an efficient method of locating the row number of the lower corner of the cube and then finding the remaining seven corners. The function lookup3d.m then finds these nodes in the output table and performs trilinear interpolation to compute the output value.

Like the majority of colour look-up table implementations, the function lookup3d.m assumes that the input table is uniformly spaced. Preliminary linearisation (as performed by the accompanying input and output tables in an ICC profile) has to be carried out separately according to the data.

As a result of this assumption, lookup3d.m does not require an input table to be supplied, as long as the input data has been pre-divided by the maxima of the input range so that the data is in the range 0-1. Alternatively, the user can supply an input table as an optional argument to the function, with the input data ranged accordingly. Because lookup3d.m does not carry out any pre-processing of the tables beyond normalisation, the input table supplied must have the same number of entries as the output table.

Utility functions

The Utility functions perform some relatively simple tasks that would be tedious to write each time they are used.

Since the current release of MatLab does not support image file formats in CIELAB colour space, it is necessary to implement a work-around for reading and writing image files. Two methods are adopted in the Toolbox:
1. Write the image as non-interleaved raw data with no headers.
2. Write the image as a TIFF file with a Photometric Interpretation tag corresponding to RGB.

The Toolbox functions carry out the scaling required to range the data correctly.

Both methods allow exchange of CIELAB data with Adobe Photoshop; with the exception of writing raw files, all operations require conversion to or from multichannel mode in Photoshop immediately prior to writing or after reading the file. Note that use of integer encodings will cause some loss of precision of the data.

For maximum efficiency, all the Toolbox functions assume that the input data is presented columnwise, with one channel per column. The M2V and V2M functions are used to convert between matrix and vector arrays to allow this columnwise processing.

Although all the functions in the Toolbox will work on arrays of unlimited size, in practice performance will suffer as system memory is used up. When working with large arrays, as is often the case with complex images, users can avoid memory issues by using the chunk function, which simply passes the input data (and up to three arguments) to the specified function in chunks of 1000 pixels.

Given an array of CIELAB data, it is often useful to be able to visualise the data directly. The function displaylabimage.m converts D50 CIELAB data to D65 sRGB (via the Bradford chromatic adaptation transform) and displays it.

A colour engineering common task is to extract colour data from an image (from a scanner or camera) of a colour target. The task requires that the image is sub-sampled to one data point per patch, discarding any patch boundaries and averaging the remainder of the pixels. Because camera images are not geometrically uniform, a simple sub-sampling can produce unwanted results. The function patchimage2data allows the user to interactively select the fraction of the patch area that can safely be retained, displaying the sub-sampled image on screen at each stage.

Psychophysics

Assessment of image quality by human observers should ideally lead to interval scales of the qualities assessed. A number of experimental techniques have been established, including pair comparison and category judgement.

The functions paircomp.m and catjudge.m compute such interval scales. Since real observer data often results in incomplete preference matrices (implying that no observers selected a particular image or category), both functions use suitable methods (Morovic, 1998; Engledrum, 2000) of estimating scores for such cases.

Rank order experiments generate ordinal data, but if the assumption is made that assigning a stimulus to a given rank implies a comparison with all the other stimuli in the experiment, then it is possible to generate corresponding pair comparison data (Cui, 2000) using a simple algorithm (Green, 2003).

Supporting functions for psychophysics include pc_seq.m, which generates a pairwise comparison sequence (either randomly or uniformly) for any number of stimuli; and two functions for plotting score data with error bars.

Use of the toolbox

 When using the toolbox, please cite: Green, P. J. (2003) ‘A Colour Engineering Toolbox’ http://www.digitalcolour.org/toolbox.htm

In order to simplify the functions only very limited error checking is performed, and users should take care to ensure that input data and associated arguments are correct.

Disclaimer

Users should confirm that the Toolbox functions are appropriate for their application and give acceptable performance. No responsibility whatever is accepted for loss or damage arising from the use or misuse of these functions, however caused.

Support

Support for the use of toolbox functions is available to currently-enrolled participants on the Postgraduate Programme in Digital Colour Imaging. The programme includes MSc, Postgraduate Diploma, Postgraduate Certificate, MSc by Project and (from September 2004) Graduate Certificate. The Msc by Project and the Graduate Certificate can be completed largely by distance learning.

Comments and updates to Dr. Phil Green, pj.green ‘at’ lcp.linst.ac.uk

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