On comparing colour spaces from a performance perspective: Application to automated classification of polished natural stones

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Outline

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2. Objectives
3. Related research
4. Materials
5. Methods
6. Experiments and results
7. Conclusions and future work

Visual appearance

- *Colour*, *texture* and *glossiness* are the three key elements that determine the appearance of materials.
- Visual appearance has a great influence on the commercial value of many industrial products: wood, ceramics, leather and natural stone are just some examples.
- Measuring the visual appearance of such materials is of the utmost importance in the industry.

Natural stone

- Overall worldwide production in excess of 76.000 tons/year.
- Typically used for cladding and tiling surfaces which are supposed to look uniform.
- Need for guaranteeing the uniformity of the visual aspect within the same lot of tiles.
- Random and highly variable colour texture: Good benchmark for machine vision algorithms.

Objectives

1. Definition of a procedure for comparing colour spaces from a performance perspective.
2. Assessment of colour descriptors and spaces for evaluating the visual appearance of materials.
3. Application to a new dataset of natural stone products.

Related research

Comparing colour spaces has generated considerable research interest since early on. Unfortunately, in most cases the results have been inconclusive or incomparable to each other.

- Adel et al. (1993): CIE Luv and CIE Lab better than Ohta's I1I2I3, HSI and RGB.
- Paschos (2001) and Rajadell and García-Sevilla (2008): CIE Lab and HSV better than RGB.

...however...

- Drimbarean and Whelan (2001): no significant difference among RGB, HSI, CIE XYZ, CIE Lab and YIQ.
- Qazi et al. (2011): for pure colours RGB and IHLS better than CIE Lab, for colour textures just the opposite.

Related research

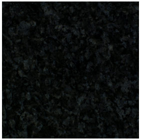
Some considerations

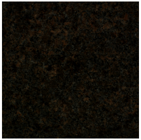
- Lack of agreement among the results available in the literature.
- Reproducing the results is very hard since data and code are rarely available.
- In most cases the experimental set-up was far from optimal. Common mistake:
    - Conversion from device-dependent to device-independent spaces performed through pre-defined formulas: likely to produce biased and erratic results.

Materials

- 25 commercial classes of marbles and granites; four samples for each class.
- Tiles of dimension 30.5cm $\times$ 30.5cm.
- Dataset freely available for future evaluations and comparisons http://dismac.dii.unipg.it/mm/ver_2_0/index.html.

Some samples


Blue Pearl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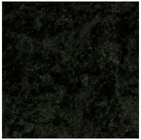
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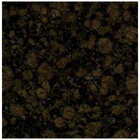
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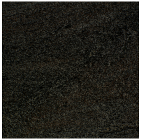
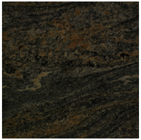
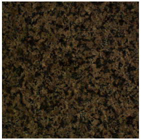
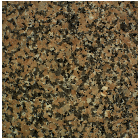
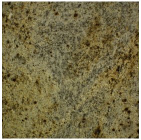

Paradiso Classico

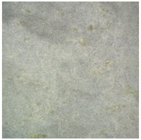

Paradiso Bash


Violetta


Rosa Porriño


Kashmir Gold


Bianco Cristal


Acquamarina

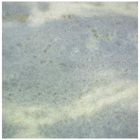

Azul Capixaba

Image acquisition
System

Problem: polished natural stones are highly reflective therefore difficult to photograph.

- Dome-shaped illuminator (Monster Dome Light 18.25").
- CMOS 1-CCD colour camera (Edmund Optics EO-5012C LE).
- 6mm fixed-focal-length lens (Pentax H614-MQ-KP)
- Base with a pocket for the tile.
- Rotatable support for the camera.

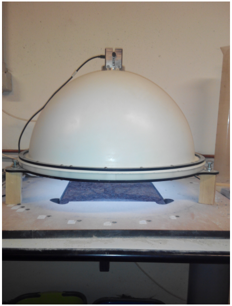


Image acquisition

Settings and procedure

To minimise the effects of reflection and glare we kept the illumination level low and compensated with the other settings (exposure time and aperture value).

- Settings:
  - Frame rate (f_r) = 2.4fps (minimum allowed).
  - General gain = 1.00×.
  - Exposure time = $1/f_r$ (maximum allowed).
  - Colour gain (from white balancing): R=14×, G=1×, B=5×.
  - Encoding: linear (no gamma correction).
- Procedure:
  - Tiles positioned along the main orientation of the veins (if present).
  - Ten images for each tile (rotation from 0° to 90°).
  - Original size: 2560px × 1920px (spatial res. ≈170dpi)
  - Centrally cropped to: 1500px × 1500px.
  - Finally subdivided into four non-overlapping images of size 750px × 750px each.
  - Illumination and camera settings invariable during the whole acquisition process.

Colour calibration rig

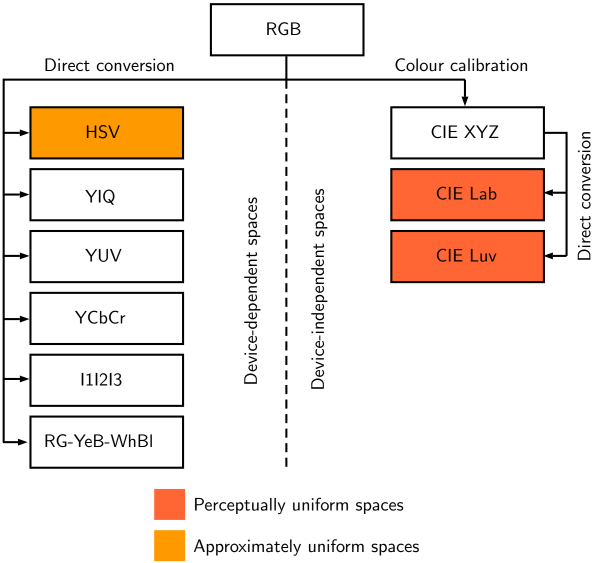
- The 140 colour samples of an X-Rite® Digital SG colour checker were also acquired using the same settings adopted for the tiles.
- The corresponding device-independent colour coordinates were measured through a Minolta CR200 Chroma Meter.

Colour

- Colour is an attribute of visual perception defined by three components (colour coordinates), e.g.: amount of *red*, *green* and *blue*; amount of *hue*, *saturation* and *intensity*, etc.
- Colour spaces may be either *device-dependent* or *device-independent*
- Conversion from device-dependent to device-independent spaces is possible only if either:
  - the spectrum of the illuminant and the response of the sensor are known;

  or
  - a calibration procedure is performed.

Colour spaces and colour conversion pipeline



Colour calibration

Model

- Problem: finding a function which transforms the colour coordinates from a device-dependent space (RGB) into a device-independendent one (CIE XYZ).
- Assumption: linear model.

$$\begin{Bmatrix} X \\ Y \\ Z \end{Bmatrix} = \begin{bmatrix} M_{11} & M_{12} & M_{13} \\ M_{21} & M_{22} & M_{23} \\ M_{31} & M_{32} & M_{33} \end{bmatrix} \cdot \begin{bmatrix} R \\ G \\ B \end{bmatrix} + \begin{Bmatrix} T_1 \\ T_2 \\ T_3 \end{Bmatrix}$$

- The 12 unknowns ($M_{i,j}$ e T_i) can be estimated through a least squares procedure.

Colour calibration

Procedure

Colour calibration

- We need a set of colour patches of which both the device-dependent and device-independent colour coordinates are known.
  - Colour patches: the 140 colour targets of the X-Rite® Digital SG colour checker;
  - Device-dependent colour coordinates: from the image acquisition system;
  - Device-independent colour coordinates: from the chroma meter.

Gamut mapping

- The eight vertices of the RGB cube (gamut) were projected into the other colour spaces considered in the experiments;
- The transformed gamuts were used to normalise the colour coordinates in each of the destination colour spaces.

Colour conversion: the 'sloppy' way

It is not uncommon for the transformation from RGB to XYZ to be performed through predefined formulas such as the following one:

$$\begin{Bmatrix} X \\ Y \\ Z \end{Bmatrix} = \begin{bmatrix} 0.412453 & 0.357580 & 0.180423 \\ 0.212671 & 0.715160 & 0.072169 \\ 0.019334 & 0.119193 & 0.950227 \end{bmatrix} \cdot \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

However, this is only valid if the red, green and blue coordinates are given in the sRGB colour space!

This approach is likely to produce biased results and should be avoided.

Colour descriptors

Soft colour descriptors: sets of statistics describing the colour content of an image. Main advantages:

- conceptually simple and easy to implement;
- low-dimensional;
- computationally fast;
- accurate.

Descriptors considered in the experiments:

- mean of each colour channel (three features);
- mean + standard dev. (six features);
- mean + 2^{nd} to 5^{th} moment (15 features);
- percentiles
  - quartiles (nine features);
  - quintiles (12 features).

Experiments

General settings

- Multi-class, supervised image classification task.
- Classifiers
  - Nearest neighbourhood (Euclidean distance);
  - Linear.

Accuracy estimation

- Random subdivision into *train* and *test* set;
- Training ratio $= 1/4$;
- Stratified sampling;
- Accuracy $=$ percentage of tiles of the test set classified correctly;
- 100-fold validation.

Results

Overall accuracy by colour spaces and descriptors

Col. space	Mean	Mean+Std	Mean+Mom.	Quartiles	Quintiles
	Classifier: *1-NN*				
CIE XYZ	82.3	90.0	85.7	90.9	91.1
CIE Lab	89.8	93.5	91.8	93.5	93.6
CIE Luv	**90.4**	94.0	**92.4**	93.9	94.0
CIE Lab*	88.0	93.8	91.0	93.0	93.3
CIE Luv*	89.1	94.1	91.8	93.8	94.1
RGB	89.1	**94.9**	91.2	94.4	**94.7**
HSV	90.0	94.1	90.0	91.7	91.3
YUV	89.1	94.1	91.6	93.5	93.7
YIQ	88.5	93.8	91.2	93.1	93.4
YCbCr	89.1	94.0	91.6	93.5	93.7
I1I2I3	89.8	**94.9**	92.3	**94.2**	94.5
RG-YeB-WhBl	89.8	**94.9**	89.8	94.1	94.4

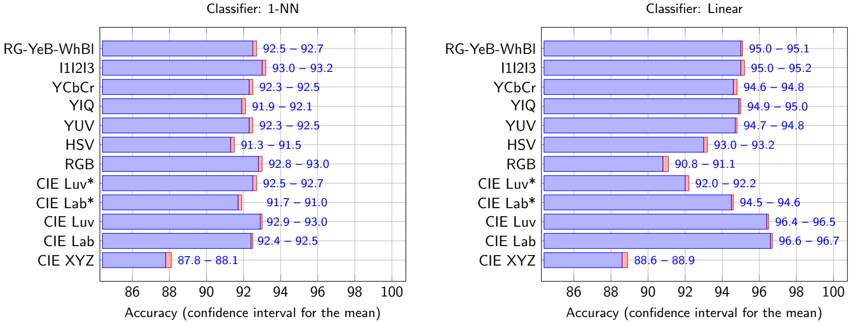
Col. space	Mean	Mean+Std	Mean+Mom.	Quartiles	Quintiles
	Classifier: *Linear*				
CIE XYZ	82.3	92.6	91.3	88.6	89.0
CIE Lab	**94.8**	**98.6**	**98.3**	**95.7**	**96.0**
CIE Luv	**94.8**	98.1	97.6	**95.7**	95.8
CIE Lab*	92.4	95.7	96.5	93.8	94.4
CIE Luv*	88.9	92.4	89.7	94.7	95.0
RGB	85.2	94.9	93.7	90.4	90.8
HSV	91.3	97.2	93.7	91.7	91.6
YUV	93.0	95.6	96.4	94.5	94.3
YIQ	93.3	95.6	96.5	94.5	95.0
YCbCr	93.0	95.6	96.3	94.2	94.4
I1I2I3	93.1	95.9	96.8	94.5	95.2
RG-YeB-WhBl	93.4	96.1	95.5	94.8	95.2

- Good accuracy (avg. $\approx$94%, max. $>$ 98%);
- Simple descriptors (e.g. mean + std. dev.) seem adequate for the task.

NOTE: Symbol '*' indicates that the conversion RGB $\rightarrow$ CIE XYZ was obtained the 'sloppy' way.

Results

Accuracy: confidence intervals for the means (by colour space)



- With the 1-NN classifier no colour space emerged as clearly superior;
- With the linear classifier CIE Lab and CIE Luv significantly outperformed the other spaces;
- Colour conversion through colour calibration works better than the 'sloppy' way.

Conclusions

- We have proposed a rigorous procedure for comparing colour spaces from a performance perspective.
- We have applied it to the problem of grading natural stone tiles.
- Under controlled illumination conditions simple colour descriptors proved adequate for the task.
- Among the colour spaces CIE Lab and CIE Luv outperformed the others with the linear classifier, whereas no signicant difference emerged with the 1-NN classifier.
- Conversion from device-dependent to device-independent spaces gave better results when performed through colour calibration than through the approximated formula ('sloppy' way).
- A hopefully useful by-product: a new and freely available dataset of natural stone images.

Final considerations and future work

- The performance of colour descriptors is likely to degrade significantly under variable illumination conditions.
- Possible ideas for future work:
  - Repeating the analysis under variable illumination conditions;
  - Considering other classification strategies (es.: k-NN, SVM, Bayesian, Random forest, etc.);
  - Using multi-spectral imaging;
  - Enlarging the experimental basis by adding new classes.

Acknowledgements

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