Avoiding Chromaticity Creep with PseudoGrey

I. J. Grimstead[1] and N. J. Avis[1]

[1]Cardiff School of Computer Science & Informatics, Cardiff University, Wales, UK

Abstract

We examine the calibration of Commodity, Off-The-Shelf (COTS) monitors to the DICOM GreyScale Display Function (GSDF) standard (as used for medical imaging). We note that uncalibrated and calibrated (using commercial and non-commercial tools) monitors exhibit "Chromaticity creep" along the black body locus in CIE 1931 colourspace; this is at odds with high-end medical monitors which do not introduce colour—but cost significantly more than COTS colour monitors. Alternative algorithms are investigated to produce a DICOM GSDF compliant calibration, where we take into account both luminance and chromaticity. Using PseudoGrey we generate thousands of shades of grey on a colour monitor to produce a high dynamic range, albeit in greyscale, improving on the standard 256 shades of grey. In this work, we now restrict our introduction of colour to minimise chromaticity deviation from a given white point. We have found various chromatic anomalies with COTS monitors, and discuss our findings along with algorithmic variations to cope with such issues. We believe this work contributes to the availability of a robust method to calibrate COTS colour monitors to the GSDF and hence any required intensity curve whilst retaining a "pure" colour, enabling greyscale images with over 256 shades to be accurately displayed. This may have significant cost, and potentially improved diagnostic implications, in the reporting of medical radiological images, and could be used to display high dynamic range greyscale imagery (such as multiple exposure black & white photography).

Categories and Subject Descriptors (according to ACM CCS): Computer Graphics [I.3.3]: Viewing algorithms—Computer Graphics [I.4.3]: Greyscale manipulation—Life and Medical Sciences [J.3.c]: Medical information systems—

1. Introduction

Medical imaging requires accurate reproduction of greys in diagnostic monitors, as used when reviewing patient X-Ray imagery for instance. To enable this, medical monitors are capable of displaying a very wide range of intensities, such as 10-bit greyscale, rather than the 8-bit range in Commodity Off-The-Shelf (COTS) monitors. However, such medical monitors are very expensive (in the range of £10,000); we would like to calibrate a COTS monitor (costing in the region of £200) to accurately display medical imagery.

Various techniques exist to calibrate COTS monitors, but these only calibrate the luminance (i.e. do not take chromaticity variance into account). In this paper we investigate approaches to calibrate a COTS monitor for both chromaticity and luminance to extend available grey shades over a high dynamic range (>256 shades), targeting the DICOM GSDF for luminance. Such a technique is also applicable to other areas, such as radar imagery, black/white photography and preprint verification, where an accurate reproduction is required on a monitor both in terms of chromaticity and intensity. We cover the background to medical display calibration in the next section, followed by related previous work. We then compare the chromaticity ranges for medical and COTS monitors, and then describe our new approaches in the following section. We then finish with our our conclusions and future work.

2. Background

Medical monitors are calibrated to the Digital Imaging and Communications in Medicine (DICOM) GreyScale Display Function (GSDF) [NEM08]. This ensures that each individual shade of grey is discernible from its immediate neighbours by being sufficiently different in brightness; this is defined using a "Just Noticeable Difference" function (JND). To achieve conformance to the GSDF, the following process is carried out (defined on page 31 of [NEM08]): a graph is

produced, showing the Digital Drive Level (DDL) against the difference in JND between the given DDL and the previous DDL (the "JND interval"). To clarify, the DDL is the digital value sent to the graphics card—so, a grey colour of (127,127,127) would be said to have a DDL of 127. Two tests are then applied; the FIT test ensures that each step in JND between DDLs is consistent, and is measured by fitting a polynomial curve through the sample points; this curve should be linear. The LUM test measures the uniformity of JND steps across the DDL range as the Root Mean Square Error (RMSE) of the curve fitted during the FIT test.

A DICOM calibration can be achieved with a COTS monitor, as the DICOM standard does not define how many shades of grey are required—just that they are uniformly discernible. Hence a COTS monitor could be said to be calibrated if it showed 20 shades of discernible grey. However, this would not show the full detail of a medical image, which is usually displayed with 256 steps in intensity. Medical monitors up until a few years ago only accepted 256 shades of grey as input, where the hardware mapped the 256 shades into a far wider palette of (e.g.) 10-bit greyscale, so selected 256 shades from a range of 1,024 (or more) to produce a DICOM GSDF calibration. It should be noted that limiting a display to 8-bit greyscale has been found to not impact negatively on diagnostic performance [KSS*07], so 8-bit image depth is still widely used. We now briefly review alternative techniques to produce a wide range of greyscales using standard (COTS) display hardware.

3. Previous Work

Given that standard graphics cards can only produce 256 DDLs, only 256 "pure" shades of grey (from black to white) can be produced, as the three colour components (red, green, blue) must be equal. However, by using off-white shades of grey, then additional levels of intensity can be introduced—at the expensive of introducing small amounts of colour.

Displaying logically incorrect colours to produce a physically correct result is the premise of PseudoGrey [TCL*92, Tyl97], where a "pure" grey such as the R,G,B triplet (130,130,130) is taken and slightly tinted with colour, producing a result such as (130,131,130). Consider the conversion from colour to greyscale using the YUV colour space presented in Equation 1.

$$Y = (0.299 \times R) + (0.587 \times G) + (0.114 \times B) \qquad (1)$$

This equation defines the relative weightings of the colours in terms of luminance (brightness) (Y). From this, it can be seen that the blue component is weighted approximately at 11%, red 29% and green 58%. So, from a given pure grey colour (R,G,B) (where $R = G = B$), changing to $(R,G,B+1)$ would produce a luminance that was roughly 11% between (R,G,B) and $(R+1,G+1,B+1)$. Such colours still appear grey to the eye, yet enable intermediate stages of luminance between neighbouring "pure" shades of grey. A sample sequence of increasing luminance could be: (130,130,130), (130,130,131), (130,130,132), (131,130,130), ... , (130,131,132), (131,131,131).

Previously, we have worked on PseudoGrey to produce a DICOM GSDF compliant display, but have not taken into account chromaticity [GAEB09, GA09]. We noted that the blue channel was highly utilised as it accounts for 11% of the intensity of a single pure grey step, so can be used for approxiately 9 steps of intensity between pure greys. Such a boost in blue intensity (+9) introduces an observable "blue" tint to pixels. Hence to produce a display that "looks" white (without observable erroneous colours), we need to take into account chromaticity during the calibration step.

Temporal dithering has been investigated [DF03, MCAB07], where consecutive frames use off-white shades (PseudoGrey), but alternate which colour component is being altered to produce the shade. Hence frame N may show (100,101,100) whilst frame $N+1$ may show (101,100,100), dithering the colours in time as well as colour space. Such a system, would require either custom hardware or a device driver change to repeatedly repaint constant colour areas with the next colour in the sequence.

Publications in the academic literature are uncommon; however, such work has appeared in many patents. The use of PseudoGrey to increase the available shades of grey is covered in [Lah02], where the different luminance contributions of the three colour components (red, green blue) are used to directly calculate intermediate steps of luminance between two neighbouring shades of pure grey. The offsets in luminance are assumed to be constant, so fractional steps between pure greys can be calculated rather than sampled.

Viewing of medical images with PseudoGrey is targeted in [WQS05], where this patent prescribes that chromaticity range should be reduced as far as possible, and should be within a threshold of the desired white point (hence contained in a cylinder in YUV colour space). However, they target a spiral in YUV colour space (akin to the CIE 1931 colour space used in this paper), so colour is used in a controlled manner. Unfortunately, the calibration method to obtain such a series of values is not revealed.

PseudoGrey is again used in [YN07], where a range of colours $(R\pm2,G\pm2,B\pm2)$ from each ''pure" grey (R,G,B) is tested as a candidate colour for suitability in terms of both luminance and chromaticity. This produces 55 candidate colours for each grey, of which the three nearest colours in terms of brightness are initially selected. One colour is then selected from the three, which is the colour nearest to the desired chromaticity value. This patent also highlights chromaticity drift as DDL is increased in a colour monitor.

4. COTS vs Medical: Comparing Monitors

The colours produced from a medical grade monitor are tightly packed in chromaticity, as they are from a

monochrome display; we were fortunate to gain partial access to a BARCO E-3620 MA monitor which we tested. Such a monitor is normally connected to a live PACS system, so we could not install any software on the host workstation, but instead temporarily connected it to a standard workstation and analysed its colour gamut, as presented in Figure 1. The range of chromaticity displayed is very small, apart from a few samples which have drifted towards lower Y in CIE space—these are dark colours which have been influenced by the room lighting in our test (made by bypassing the device's luminance calibration).

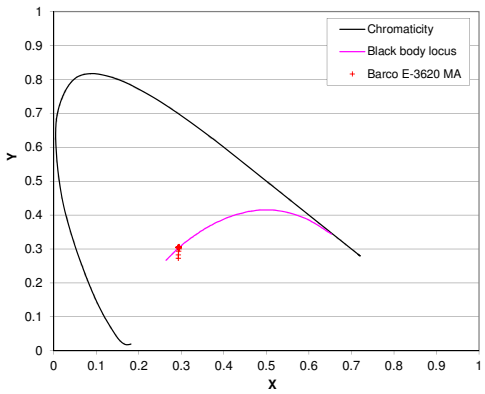

Figure 1: *Chromaticity analysis of a Barco E-3620 MA medical monitor using CIE 1931 colour space*

This may be compared to an uncalibrated COTS monitor, such as a DELL AS500; to test a monitor, we place the monitor under a 4m long "light tent", where ambient light is blocked by a heavy black curtain, with the monitor at one end and a Konica Minolta CS-200 ChromaMeter at the other. The chromameter is set to use a 2 degree sample angle, and is focused on the middle of the screen. Custom software produces a series of test colours on the monitor, subsequently sampled by the chromameter, and the results recorded for analysis as (R,G,B) triplets (in the range 0..255) against CIE 1931 colourspace (L,x,y) triplets (L being cd/m^2, and x,y the normalised CIE coordinates in the range 0-1).

A DELL AS500 monitor was tested for chromaticity variation through its range of greys (from white to black). The chromaticity is shown in Figure 2, with pure red (255,0,0), green (0,255,0) and blue (0,0,255) also sampled to give context to the grey samples. In addition, the "black body locus" is also shown—representing the colour a perfect black body should produce when it is heated from $1,000\,^{\circ}$K to $15,000\,^{\circ}$K. The DELL AS500 exhibits a wide colour gamut when displaying levels of grey from (0,0,0) to (255,255,255), showing that colours follow the black body locus, albeit in reverse—the brighter colours tend towards red, rather than a true black body where hotter (observed as brighter) colours tend towards blue. Zooming in on the chromaticity data (Figure 3), the scattering effect of dark colours can be seen—these are scattered in a circular pattern around the main body of sample points. The sample points otherwise form a linear pattern in CIE colourspace.

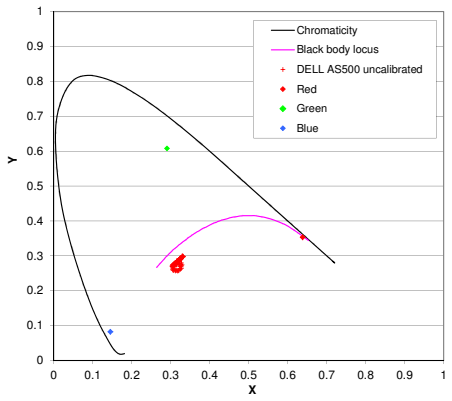

Figure 2: *Chromaticity analysis of a DELL AS500 COTS monitor using CIE 1931 colour space*

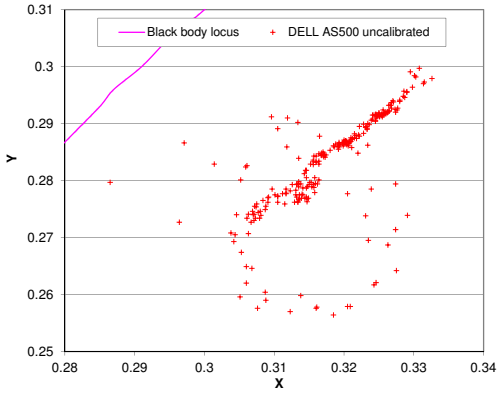

Figure 3: *Zoomed in view of chromaticity analysis of a DELL AS500 COTS monitor graphed with CIE 1931 colour space*

From this data, it can be seen that a COTS monitor needs careful calibration before its chromaticity range is restricted to approach that of a medical monitor. Several devices exist in the market for calibrating COTS monitors, consisting of a "sucker cup" chromameter which samples the light output from the monitor, and appropriate calibration software to drive it. Such software is designed to correct luminance, however, and not to restrict the chromaticity range. We have tested two such devices, and both produce chromaticity ranges similar to each other, of which we present one in Figure 4. It can be seen to be remarkably similar to that of the uncalibrated state of the monitor, yet the luminance is calibrated. It suggests that the brightness of the

colour is only changed, such as using the gamma control in the DirectX driver under Microsoft Windows. This still exhibits the trend of brighter colours towards red, as opposed to the black body locus where hotter (therefore brighter) colours tend towards blue.

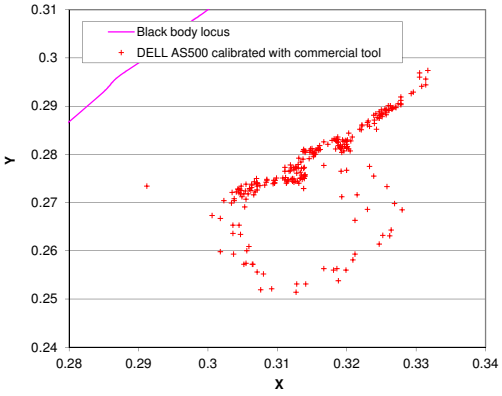

Figure 4: *Zoomed in view of chromaticity analysis of a DELL AS500 COTS monitor calibrated with a commercial tool, graphed with CIE 1931 colour space*

5. Optimising PseudoGrey to Reduce Chromaticity Range

In this section we examine the optimisation problem underlying the reduction of chromaticity range, with several approaches to achieve this and the issues we faced in practice.

5.1. Optimisation Problem

In outline, we simply wish to select a triplet of values (R,G,B) that produce a given brightness and colour value on a given monitor. Our optimisation problem is thus to minimise two coupled variables: the error in luminance whilst simultaneously minimising the error in chromaticity.

However, this is actually a challenging optimisation space. The variables (R,G,B) are all independent, and are discrete. The measured outputs (L,x,y) are non-linear, and subject to environmental factors (such as the effects of ambient light). We can remove the ambient light variant through controlling the test environment's lighting condition, but the other problems must be considered in a calibration algorithm. The non-linearity is highlighted in Figure 5, where each "pure" colour is sampled in CIE 1931 chromaticity space. "Pure" colour is used to refer to colours consisting of uniform component DDLs or zero DDL, such as (20,20,0) or (50,0,50). Such triplets produce the colours red $(N,0,0)$, yellow $(N,N,0)$, green $(0,N,0)$, cyan $(0,N,N)$, blue $(0,0,N)$ and magenta $(N,0,N)$ (ignoring white for the present). Note that the colours which use two colour components (namely: cyan, yellow, magenta) follow a distinctly non-linear path when the DDL is increased; compare the paths against the arrows overlaid in Figure 5.

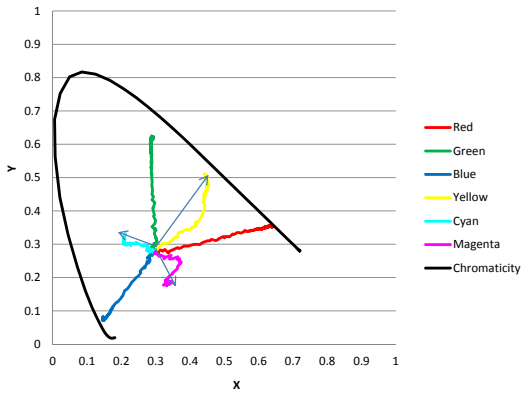

Figure 5: *View of chromaticity for major colours from black to maximum intensity of a DELL AS500 COTS monitor graphed with CIE 1931 colour space*

In the following algorithms, we measured the maximum brightness and minimum brightness the monitor could achieve. Using the concept of "Just Noticeable Difference" (JND) from the DICOM standard [NEM08], we define the JND value from a given luminance (in cd/m^2) in Equation 2. $j(L)$ returns the JND of a given luminance value L (in cd/m^2), and A,B,C,D,E,F,G,H and I are constants defined in Section 7.1 "General Formulas" on page 12 in [NEM08].

$$\begin{aligned} j(L) \;=\; & A + B\cdot Log_{10}(L) + C\cdot (Log_{10}(L))^2 \\ & + D\cdot (Log_{10}(L))^3 + E\cdot (Log_{10}(L))^4 \\ & + F\cdot (Log_{10}(L))^5 + G\cdot (Log_{10}(L))^6 \\ & + H\cdot (Log_{10}(L))^7 + I\cdot (Log_{10}(L))^8 \end{aligned} \qquad (2)$$

To produce a DICOM calibration, the displayed shades of grey must be at least one JND apart to be noticeable by a human observer. Depending on the brightness of the monitor, it may be capable of displaying in excess of 256 JNDs. However, we restrict ourselves to 256 shades of grey, so distribute the intensities evenly throughout the JND space. The algorithm must then find colours which produce the required brightness whilst producing chromaticity close to the desired white point.

5.2. Naive Search Algorithm

Our first attempt at an algorithm was a naive search, with the "previous colour" seeded as being black:

1. Start from previous colour defined as (R,G,B).
2. Display neighbouring colours and sample for luminance and chromaticity (whilst not resampling any previously tested colours), starting with $step = 8$:

a. Scan $(R+step, G, B)$
b. Scan $(R-step, G, B)$
c. Scan $(R, G+step, B)$
d. Scan $(R, G-step, B)$
e. Scan $(R, G, B+step)$
f. Scan $(R, G, B-step)$

3. If tested colour reduces error in luminance and produces chromaticity within threshold of target white point, store tested colour as best result.
4. If a new colour was selected then recursively scan from the new colour, otherwise reduce $step$ and iterate until $step = 0$.

This algorithm is simple in that it does not take into consideration the direction (in CIE 1931 colour space) that the tests are heading—it can be testing values that are making the luminance and chromaticity error worse.

Initial results obtained by conducting a simulation appeared promising, giving a tight bound on chromaticity values but a wide variance of luminance values. However, trying the algorithm on a real monitor caused it to fail by repeatedly hitting local minima from which it could not escape (e.g. continuously failing to find an improvement on the previous colour).

The results were examined carefully, where we noticed that the monitor was not behaving as expected; an increase in DDL in a colour did not necessarily result in an increase in luminance (as assumed, for instance, by [Lah02]). Pure red, green, blue and grey colours were displayed, and the luminance measured. Ambient light was taken to be constant, and removed from the luminance values obtained. Red, green and blue were compared as a fraction of luminance of pure grey. The sum of these fractions would (naively) sum to be 1.0, given that grey is produced by even DDLs in red, green and blue. The sum of the fraction was hence also graphed, all of which is presented in Figure 6.

From this analysis, it can be seen that low DDLs produce very irregular results (see the ringed area on the left of the graph), such as red luminance being higher than green—which is at odds with Equation 1. YUV to RGB conversion suggests that red should contribute 29% whilst green 58%. In addition, high DDLs (the ringed area on the right of the graph) also produce unexpected results, where the intensity of red decreases its contribution whilst green increases. In addition, the luminance levels to the right of the initial "noisy" results are also strange—the red contribution quickly settles to a constant value, but the green contribution slowly climbs as the DDL increases.

Further, if we measure the luminance per DDL and compare between channels (see Figure 7), it can be seen that high DDL values do not produce a uniform change in brightness (refer to the ringed area in the graph). Red DDLs in the region of 240 onwards do not produce an increase in luminance at all—this may be the result of a faulty monitor, but as we wish to cope with any monitor "in the field", this behaviour must be taken into consideration.

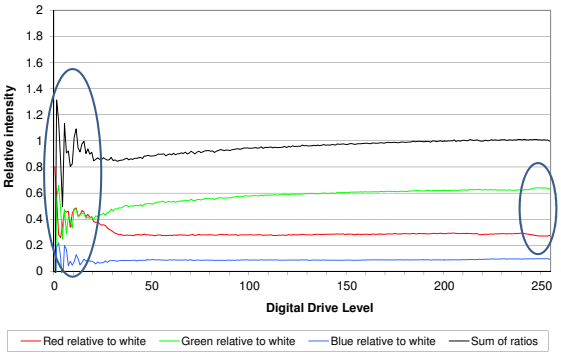

Figure 6: *Luminance analysis of an uncalibrated DELL AS500 COTS monitor; relative values of pure red, green, blue and grey colours were compared in luminance.*

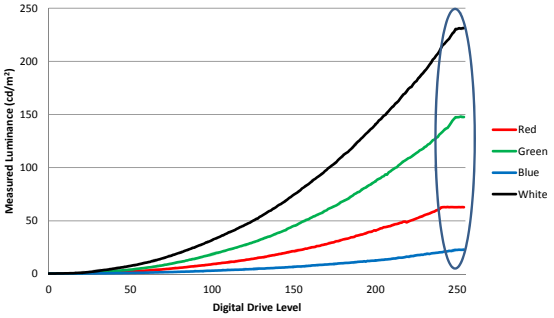

Figure 7: *Luminance analysis of an uncalibrated DELL AS500 COTS monitor; pure red, green, blue and grey colours were compared in luminance.*

5.3. Directed Search Algorithm

Given the issues with local minima in the naive algorithm, we designed an improved algorithm that would take into account both luminance and chromaticity, and would attempt to take a colour step that would improve both error measures.

The basis of the algorithm is to work out if a step in R, G or B will move the current sample nearer towards the white point or away. If (for example) a step of (+1,0,0) or (0,-1,-1) increases the amount of red in the current sample—one would increase the overall brightness of the sample, the other step decreases the brightness. Hence we can select a change

in (R,G,B) that should move the sample towards both the target chromaticity and target luminance.

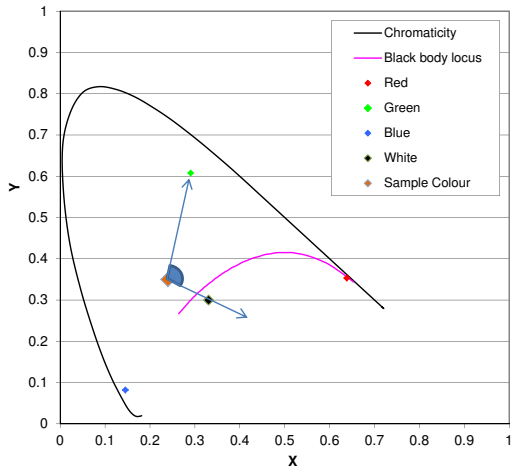

Figure 8: *Directed Algorithm: sample point compared to green point and white point.*

We display "pure" white (255,255,255), red (255,0,0), green (0,255,0) and blue (0,0,255) and measure the luminance and chromaticity in CIE 1931 colour space. We define these to be our red point, green point, blue point and white point respectively—as they are the maximum intensity of each colour we can produce. A vector is calculated from the current sample colour towards the white point, and towards the red point. The dot product between these vectors estimates if a step towards pure red will move the current sample towards the white point or away from it, in terms of chromaticity (refer to Figure 8 for an example). This assumes that increasing the DDL of the red component will move the sample point towards the red point. The algorithm is presented below, noting that the same calculation is then carried out for the green and blue points, with the tested point kept if it reduces our chromaticity and luminance errors. The algorithm iterates over the target JND range:

1. Find nearest pure grey that has luminance just below the target JND luminance (provides a seed value).
2. Best sample (R,G,B) is set to be the nearest pure grey.
3. Iterate with red, green and blue points:
   a. Calculate CIE vector from best sample to white point.
   b. Calculate CIE vector from best sample to red point.
   c. Calculate dot product between the two vectors.
   d. If the dot product is positive, then a step towards red moves us nearer to the white point:
      - If best sample is brighter than target JND luminance, test $(R,G-1,B-1)$.
      - else best sample is darker: test $(R+1,G,B)$.
   e. else a step away moves us towards the white point:
      - If best sample is brighter than target JND luminance, test $(R-1,G,B)$.
      - else best sample is darker: test $(R,G+1,B+1)$.
   f. If test sample reduces JND error and has chromaticity error within threshold, overwrite best sample with test sample.
4. Until we no longer reduce our JND and chromaticity errors; best sample is used for current target JND.

The results of using the algorithm on the DELL AS-500 monitor are shown in Figure 9. The algorithm was seeded with a white point inf CIE colourspace of (0.32, 0.32), and a threshold of 0.01 was set. The chromaticity samples are clustering around our desired white point.

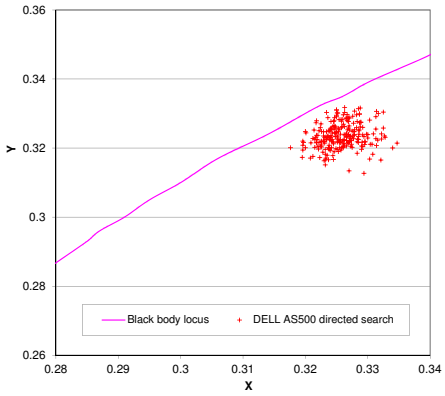

Figure 9: *DELL AS-500 monitor greyscale analysis, calibrated using directed algorithm and a threshold of 0.01 chromaticity.*

However, when a FIT/LUM test is applied to the luminance recorded, the luminance is seen to be scattered; refer to Figure 10. 9,428 samples were taken to obtain this result.

5.4. Directed Enumeration

Given the limitations of the results obtained by the directed algorithm, an unrestricted oversampling algorithm was implemented. The nearest pure grey (R,G,B) was found for a desired JND, then the colour space surrounding the grey was fully sampled (restricted to be between the luminance values of two neighbouring pure greys, darker and lighter, than our selected pure grey). Using the relative weightings of red, green and blue from the YUV to RGB colourspace conversion, samples were taken to fully enumerate from $(R-4,G-3,B-11)$ to $(R+4,G+3,B+11)$. For instance, red contributes 29% of the luminance to grey, so four steps in red should produce $\sim 118\%$ of the luminance between the neighbouring grey levels. The full enumeration will cover all possible combinations of PseudoGrey that produce luminance between the neighbouring grey shades, including

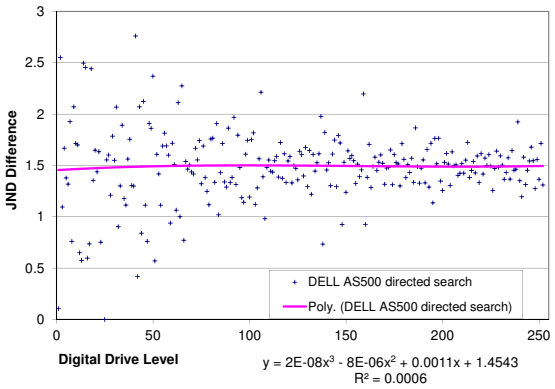

Figure 10: *DELL AS-500 monitor DICOM FIT/LUM test, calibrated using directed algorithm and a threshold of 0.01 chromaticity.*

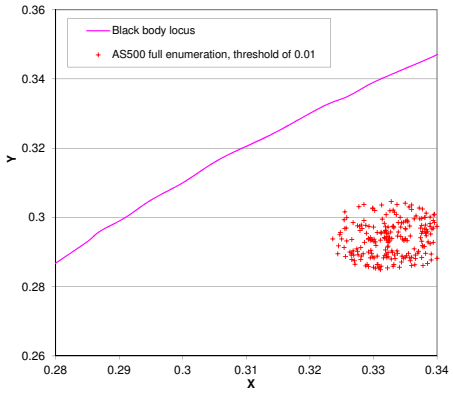

Figure 11: *DELL AS-500 monitor greyscale analysis, calibrated using directed enumeration algorithm and a threshold of 0.01 chromaticity.*

ranges not considered by the previous PseudoGrey approach [GA09] such as negative and positive steps combined, such as $(R-2, G+2, B-6)$. The algorithm is as follows:

1. Start with (255,255,255) as the best sample.
2. Iterate for each target JND:
   a. Sample the luminance of the best sample.
   b. If luminance is brighter than JND darker, use $(R-1, G-1, B-1)$ as best sample.
3. The best sample (R, G, B) is used as the basis for the scan.
4. Loop R from R-4 to R+4; G from G-2 to G+2; B from B-11 to B+11:
   a. Sample test colour (R, G, B) for luminance and chromaticity.
   b. If luminance error is lower than best sample and chromaticity error is lower than threshold, overwrite best sample with test sample.

The results of using the algorithm on the DELL AS-500 monitor are shown in Figure 11. To verify that a different white point can be used, the algorithm was instead seeded with a white point of (0.33, 0.299), with a threshold of 0.01. Again, the chromaticity samples are clustering around our desired white point.

When a FIT/LUM test is applied to the luminance recorded, the luminance is seen to be much improved; refer to Figure 12. Note that there a few outliers in the sampled data, which has biased the FIT test to produce a curve rather than a straight line. However, in total 90,224 samples were taken to produce this result (approximately a ten-fold increase compared to the directed search algorithm). Physical samples taken by the algorithm were cached and recycled to reduce unnecessary chromameter sampling overhead, but the algorithm still took in excess of 5 hours to complete.

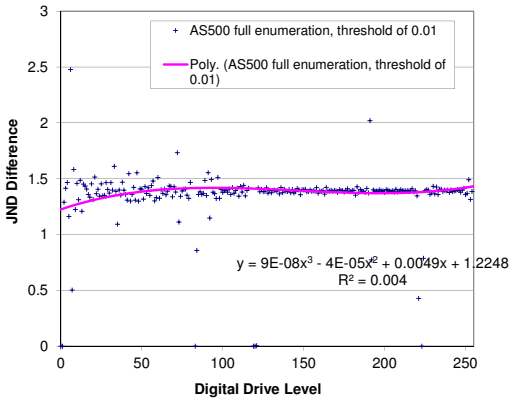

Figure 12: *DELL AS-500 monitor DICOM FIT/LUM test, calibrated using directed enumeration algorithm and a threshold of 0.01 chromaticity.*

5.5. Discussion of Results

The algorithms presented take chromatic anomalies into account, and hence work on a COTS monitor that may not have consistent luminance levels (unlike medical grade monitors). However, we have only tested a single COTS monitor—further tests need to be carried out with a selection of monitors and projectors; this may reveal additional varieties of chromatic error.

The directed enumeration algorithm uses in excess of 90,000 samples to produce its results (taking in excess of 5 hours), which is clearly inefficient. Further work is required to reduce the number of samples, whilst bearing in mind the anomalies encountered when assuming the relationship between DDL and measured luminance. In addition, outlying values have crept into the results which have skewed the FIT and LUM tests.

Note that with a JND calibration, each shade of grey is designed to be noticeably different by a human observer, and is restricted by the maximum brightness of the monitor. However, with a visual application where we do not want noticeable steps in intensity, we are free to use any shade of grey. We have 90,000 samples to choose from—if we cull samples to ensure they are within a given threshold of a specified "white" point, we expect the available shades of grey to be in excess of 5,000.

Our results suggest that a COTS monitor can be used reliably for viewing medical images. Note that we can only suggest "approximately DICOM" as the required tolerances for FIT and LUM tests are not explicitly defined in the DICOM standard, instead left defined as "Clinical practice is expected to determine the tolerances for the FIT and LUM values". However, we feel that our approach shows promise given a near-linear result from the FIT test and a minimum of one JND between each intensity of the LUM test.

6. Conclusions

We have created a test framework, in which we can test different algorithms for DICOM GSDF calibration and chromaticity analysis. The algorithms presented in this paper present an alternative approach that avoid the colour tint issue present in our earlier work on PseudoGrey. The earlier work relied on boosting the blue channel for fine luminance steps, so a blue tint was introduced to the image.

We have produced a "gold standard" through use of a high-end chromameter, but this would be unlikely to be used in practice. The algorithms should work with a COTS chromameter, when our technique would produce results that exceed that of current commercial calibration packages.

Our algorithm targeted the chromaticity within a threshold of a given white point, but does not have to be restricted so. The algorithm could target any colour within the chromaticity range of the display device—provided there are sufficient neighbouring colours supported by the device to create the required intensity ramp.

Finally, we have artificially restricted ourselves to 256 levels of grey, but (with the directed enumeration algorithm) examine in excess of 90,000 shades of PseudoGrey which have potential to be used for high dynamic range greyscale imagery (such as multiple exposure black & white photography).

7. Future Work

We wish to compare our COTS output with that of a DICOM calibrated medical-grade monitor, to verify if indeed we are reaching a comparable standard (on the FIT and LUM measurements). We have yet to secure adequate access to such a monitor under controlled lighting conditions.

Given the high cost of the Konica Minolta chromameter we have used, we wish to confirm our results using a COTS chromameter (usually costing around £70). Medical grade monitors are specially constructed to provide a near-uniform intensity when viewed off-axis (i.e. the viewer is not perpendicular to the display), with each pixel being treated to given even luminance across the display. Given such issues (which are not corrected with COTS monitors, human observer tests will be required to determine how closely a COTS monitor can meet the same standard as a medical monitor.

8. Acknowledgements

This work was made possible initially through the support of VizNET and related funding from JISC and latterly through support from the Research Institute of Visual Computing (RIVIC), funded by Welsh Assembly Government.

References

[DF03] DALY S., FENG X.: Bit-depth extension using spatiotemporal microdither based on models of the equivalent input noise of the visual system. In *Proceedings of SPIE Electronic Imaging 2003 (SPIE Vol. 5008)* (2003). 2

[GA09] GRIMSTEAD I. J., AVIS N. J.: Calibrating a COTS Monitor to DICOM Standard. In *Proceedings of EuroGraphics-UK Theory and Practice of Computer Graphics, Cardiff, UK* (2009), EuroGraphics. 2, 7

[GAEB09] GRIMSTEAD I. J., AVIS N. J., EVANS P. L., BOCCA A.: High-Quality Remote Interactive Imaging in the Operating Theatre. In *Proceedings of SPIE Medical Imaging 2009* (2009). 2

[KSS*07] KRUPINSKI E. A., SIDDIQUI K., SIEGEL E., SHRESTHA R., GRANT E., ROEHRIG H., FAN J.: Influence of 8-bit vs 11-bit Digital Displays on Observer Performance and Visual Search: A Multi-Center Evaluation. In *Proceedings of SPIE Medical Imaging 2007 (SPIE Vol. 6515)* (2007). 2

[Lah02] LAHTINEN A.: *Method and Device for Converting a Grey Scale Image into a Pseudogrey Image*. World Patent WO0239724 (A1), May 2002. 2, 5

[MCAB07] MONTE D. D., CASALE C., ALBANI L., BONFIGLIO S.: Grayscale Standard Display Function on LCD Color Monitors. In *Proceedings of SPIE Medical Imaging 2007 (SPIE Vol. 6515)* (2007). 2

[NEM08] NEMA: *Digital Imaging and Communications in Medicine (DICOM) Part 14: Grayscale Standard Display Function*. Tech. rep., National Electrical Manufacturers Association, 2008. 1, 4

[TCL*92] TYLER C. W., CHAN H., LIU L., MCBRIDE B., KONTSEVICH L. L.: Bit-stealing: How to get 1786 or more grey levels from an 8-bit color monitor. In *Proceedings of SPIE 1666* (1992), pp. 351–364. 2

[Tyl97] TYLER C. W.: Colour bit-stealing to enhance the luminance resolution of digital displays on a single pixel basis. *Spatial Vision 10* (1997), 369–377. 2

[WQS05] WEIBRECHT M., QUADFLIEG P., SPECKOWIUS G.: *Method of Reproducing a Gray Scale Image in Colors*. US Patent 6,906,727 B2, June 2005. 2

[YN07] YAMANO A., NAKAZAWA M.: *Image Processing Method and Image Processing Apparatus*. US Patent 2007/0274586 A1, Konica Minolta Medtical & Graphic, Inc., Tokyo (JP), Nov. 2007. 2