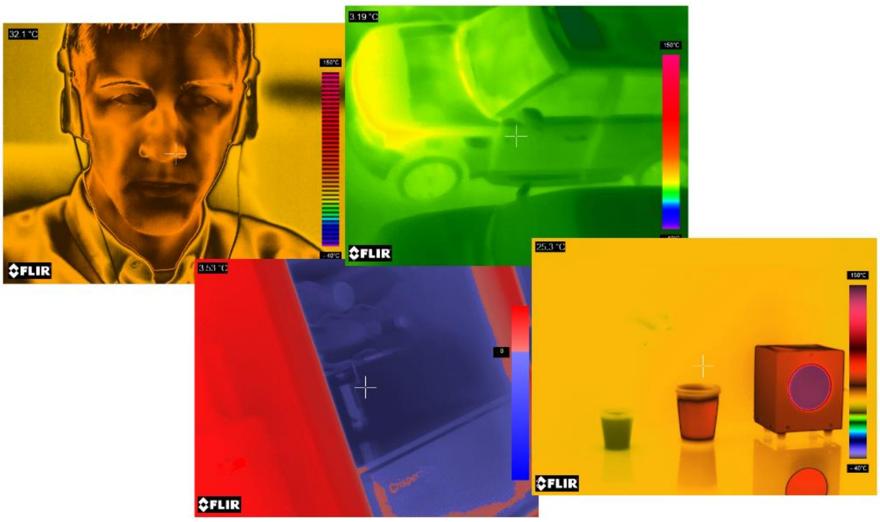
Intuitive Colorization of Temperature in Thermal Cameras

Petter Sundin



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	Examensarbete TTFYM-TFYE **Intuitiv färgläggning av temperatur i värmekameror** Petter Sundin	
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	Uppdragsgivare FLIR Systems Inc.	

Sammanfattning

Denna masteruppsats har genomförts hos FLIR Systems och har som mål att skapa en intuitiv färgläggning av värmekamerabilder där en konstant färg till temperaturkoppling uppnås. Idag är färgläggningen anpassad för erfarna användare som har gått kurser i termografi medan nya användare kan ha svårt att ta till sig informationen från kameran och göra misstolkningar. Rapporten inleds med en kort beskrivning av situationen idag och en teoretisk bakgrund som beskriver informationsflödet från ett objekt som strålar infraröd strålning till hur denna data presenteras på en skärm för användaren. Metod, resultat och diskussion är uppdelade i två delar. Första delen täcker en generisk lösning som är tänkt att fungera i en stor variation av miljöer. Den andra delen täcker en mer applikationsanpassad lösning som är riktat mot användare som har ett tydligt mål med sin användning: kontroll av livsmedel. Resultaten av utvärderingarna av de generiska lösningarna visar att lösningarna som presenteras i rapporten uppfattas som lite mindre intuitiva än dagens lösningar men kontrasten uppfattades av många som bättre och den konstanta temperatur till färgkopplingen uppskattades och förstods av många. De applikationsspecifika lösningarna uppskattades för sin förmåga att göra det lättare att utföra specifika uppgifter eftersom kameran var specifikt anpassad för just dessa uppgifter. Det är av intresse att skapa fler applikationsanpassade lösningar för att kunna nå ut på en marknad med personer utan tidigare erfarenhet av värmekameror.

	Master of Science Thesis TTFYM-TFYE **Intuitive Colorization of Temperature in Thermal Cameras** Petter Sundin	
Approved 2015-02-16	Examiner Kjell Carlsson	Supervisor Mikael Erlandsson
	Commissioner FLIR Systems Inc.	

Abstract

This master thesis, performed at FLIR Systems is aiming to create a more intuitive way of colorizing images originating from thermal cameras and creating a fixed color to temperature connection. The colorizing today is well suited for experienced users but non-experienced users often lacks the needed knowledge to be able to fully understand what the camera displays. The report starts with a short description of the current situation and a theoretical background covering the information flow from object emitting infrared radiation to how this information can be presented to a user on a screen. The method, result and discussion are divided into two parts. The first part covers generic solutions which are created to function in a variety of environments. The second part covers application specific solutions which are more aimed towards application specific needs, specifically food inspection. The results from the generic evaluation showed that the solutions presented in this report was experienced as a little less intuitive than the solutions existing today but the contrast was regarded as better and the fixed color to temperature connection was appreciated and understood by many. The application specific solution evaluation showed that the users appreciated the custom-made design and they experienced that it helped them to perform their task more than the solutions existing today would have. It is of great interest to create more application specific solutions to increase sales on the market where the customer lacks prior experience of thermal cameras.

Foreword

This master thesis aims at creating an intuitive colorization of images created by thermal cameras. It is carried out with the aim of achieving an absolute connection between a specific temperature and a specific color. The result of this, is that a user who sees a certain color should immediately understand roughly the temperature of this object based solely on the color. This would make the colorization much more intuitive than it is today. This thesis also contains a section with the goal of creating a colorization suitable for application specific solutions, such as food inspection.

I wish to thank my supervisor at FLIR, Mikael Erlandsson for his ideas, support and encouragement. I would also like to thank Fredrik von Braun for his ideas, Christian Högstedt for the car rides to the local lunch restaurants, Martin Solli and Stefan Olsson for help with Matlab and all my test subjects for their time.

Petter Sundin
Stockholm, February 2015

Nomenclature

Chrominance	Color information of an image
Luminance	Brightness of an image
Palette	Look up table for colorizing IR images
Temperature range	Maximum and minimum measurable temperature by a camera
Temperature span	Current temperature span that the camera measures in

Notations

Symbol	Description
λ	Wavelength of photons
h	Planck's constant, $6{,}6261 \cdot 10^{-34}$ Js
c	Speed of light, 299 792 458 m/s
σ	Stefan Boltzmann constant $5{,}670373 \cdot 10^{-8}\ Js^{-1}m^{-2}K^{-4}$
ε	Emissivity of a material
τ	Transmission of a material
ρ	Reflection of a material

Abbreviations

FLIR	Forward looking infrared
HSV	Hue, Saturation, Value
IR	Infrared
JND	Just Noticeable Difference
NETD	Noise Equivalent Temperature Difference
RGB	Red Green Blue

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1 Introduction

1.1 Background

This master thesis has been performed at FLIR Systems Inc. FLIR is located in Täby, Sweden and is a manufacturer of thermal cameras. A thermal camera is a device made to capture infrared radiation, functioning much like an ordinary camera except that it operates in a different region of the electromagnetic spectrum. The intended use for thermal cameras can vary greatly and its application possibilities are many.

In most thermal cameras today, there is no standardized way of colorizing infrared images. This can cause problems when a novice user interprets an image. This is of course an issue as the user has to be able to trust what the camera displays. The displayed image is usually colorized in a relative/automatic color scale, this color scale is also known as a palette. The palette colorizes the pixels depending on their relative values based on the temperature currently captured by the detector instead of their absolute temperature value. When a user aims a thermal camera towards an object with a specific temperature, the palette will colorize this object depending on the object surrounding it and the current dynamic temperature range. Figure 1 shows how the visualization of a computer mouse is affected by the surrounding objects and their temperature. In Figure 1a, the mouse is the hottest object in the scene and is therefore colorized in such a manner. In Figure 1b, a hot transformer is visible to the right of the mouse, and because the transformer is hotter than the mouse, the mouse will appear to be much colder in the right picture even though it has the same temperature in both images.

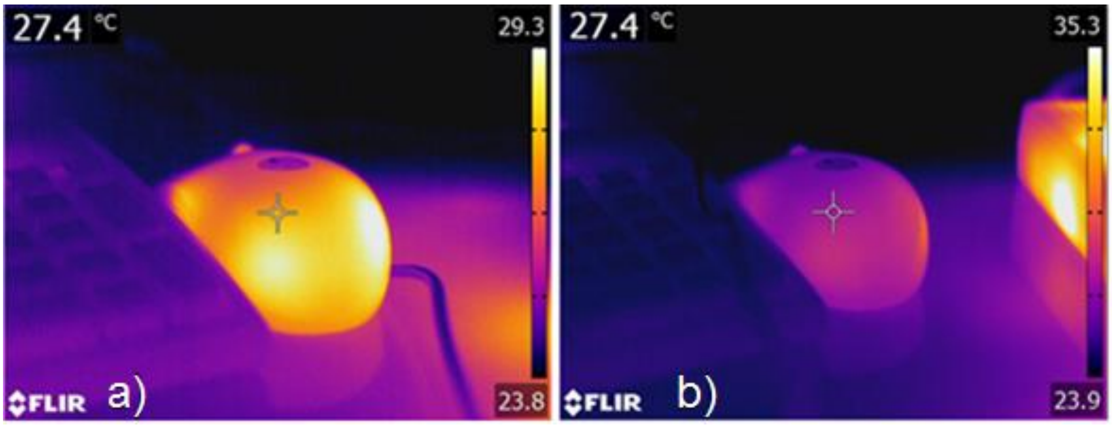


Figure 1: The same computer mouse in both images with the same temperature, colorized in different colors even though they have the same temperature. a) The mouse is the hottest object in the scene. b) a transformer is the hottest object in the scene.

Figure 1 demonstrates the problem, the relative scale makes the user draw wrong conclusions based on the color inconsistency. Figure 1 is colorized with the popular palette *Iron*. It is technically possible today to lock the palette to a selected temperature span and then in a sense locking the colors in the palette to certain temperatures. This is however something that requires a very experienced user and is therefore rarely used. It requires the user to be familiar with the camera software, have a clear understanding of what he or she is looking at and understand what happens when objects in the scene have a temperature that is outside the temperature span. What will happen when the user locks the temperature and palette between for example 10 °C and 25 °C and then an object, say a person's hand is introduced into the image, is that this hand seems to be 25 °C even though it is probably closer to 30 °C.

Objects with temperatures that are outside the user defined span will appear to have a temperature at either the max temperature of the span or the minimum temperature, depending on if the object temperature are higher or lower than the temperature spans maximum and minimum. The color that objects outside the current temperature span are colorized in are called saturation colors and are usually the colors in the endpoints of the palette.

Figure 2: The iron palette is locked in the span 15 °C to 25 °C. Because the hand is warmer than 25 °C, it is colorized as white, with no contrast.

In Figure 2, an image of a hand where the temperature has been locked to a temperature span is seen. The hand contains no details or contrast because every texture on the hand is warmer than 25 °C, and will thus all be colorized in white. It is impossible to see any difference between objects at 26 °C and objects at 126 °C because they will both be colorized with the saturation color. This can be a source of error and can even be dangerous if the user is fooled to believe that some dangerously hot object is safe to touch and work with.

1.2 Purpose and goals

The purpose of this master thesis is to find new ways of colorizing infrared images to make it more intuitive so that a novice user is able to pick up an infrared camera and use it right away. The user should not be forced to go through training sessions and lectures just to be able to use a camera in a simple way. Several concepts are developed and tested. Selected concepts are then customized to fit certain user needs. Finally, the concepts are evaluated on representative users, both experienced users and non-experienced novice users.

1.3 Scope

This master thesis project aims at fulfilling these important criteria:

1. There should be a connection between an absolute temperature and a specific color component. If the user sees a color, this color should be associated with a specific temperature, always.
2. The contrast in the image should be so good that damp stains in buildings should be easily detectable in images with large dynamic span. The contrast should be comparable to the contrast in existing cameras available today.
3. The images should be intuitive and the user should be able to understand what the image displays without extensive training. The final concepts should support walk up use.

The developed prototypes are not hardcoded into a camera, only implemented on a PC running Matlab with an IR camera connected through an internet cable. The IR camera streams a live feed of images containing radiological data that Matlab then processes. The specific camera used is a FLIR A615 (specifications can be found in appendix C) without display which are normally used for safety and automation purposes.

2 Theoretical background

The theoretical background of this thesis begins with a brief description of the company at which the thesis was carried out. The sections after describe the flow of information in an IR camera where each step is explained (Figure 3). From the object emitting the radiation to how the user sees the image on a display and how humans interpret this information presented to them.

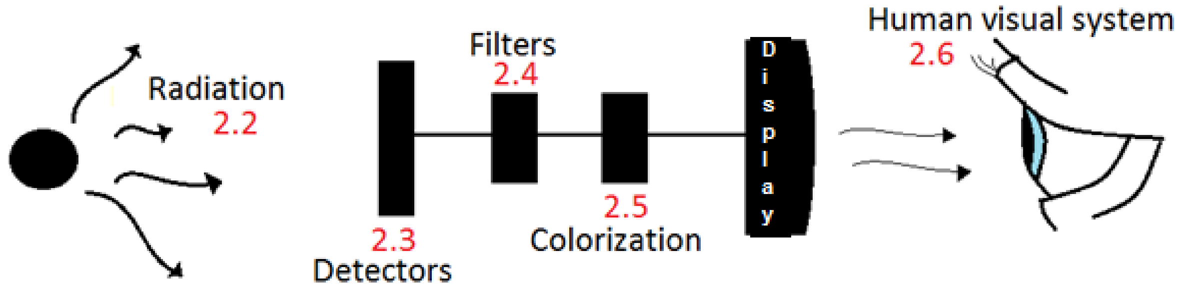


Figure 3: The layout of the theoretical background.

2.1 About FLIR Systems Inc.

FLIR employs around 3000 people worldwide with two major manufacturing plants in Oregon and Massachusetts, US and one in Stockholm, Sweden. The revenues in 2011 was $1.4 Billion which places them on number 37 in the *Forbes top 200 best small companies in* the US. (Flir, 2014) FLIR Systems Inc. was formed in 1978 and is the largest manufacturer in the world of thermal cameras. The application possibilities of their products are very broad and covers many areas. The company is divided into six segments:

- **Surveillance segment**
  Specializing in recognition and imaging for the military, public safety, law enforcement, border control and other governmental use
- **Instruments segment**
  Products for industrial, commercial and scientific applications that measures thermal energy and other environmental elements
- **OEM and emerging markets segment**
  Creates components intended for third parties to create their own thermal systems, develops traffic systems and systems for law enforcements that can be mounted on weapons or handheld by troops
- **Maritime segment**
  Recreational and commercial maritime products
- **Security segment**
  Video recording systems and cameras intended to be used for security in infrastructure, at home or commercial use
- **Detection segment**
  Sensors and instruments for identification of chemical, radiological, biological and nuclear explosive threats

2.2 Radiation

Humans can only see radiation within the visible range of the electromagnetic spectrum, 380nm to 780nm in wavelengths of light. The infrared region starts where the human eyes capability ends and stretches up to about 1mm. Infrared radiation is therefore invisible to the human eye and has longer wavelength than visible light. There are however studies where humans have been able to see light with wavelength up to 1065nm, which is in fact in the realm of infrared radiation. (Sliney *et al.*, 1976)

IR radiation was discovered by William Herschel in 1800 when he performed experiments on thermometers and the effects of different wavelengths of light had on the temperature. He discovered that there had to be some invisible light that caused the thermometer to rise in temperature. (Rogalski, 2010)

Figure 4 shows the simplified electromagnetic spectrum. Every molecule that is in some kind of motion emits infrared radiation based on its molecular vibration.

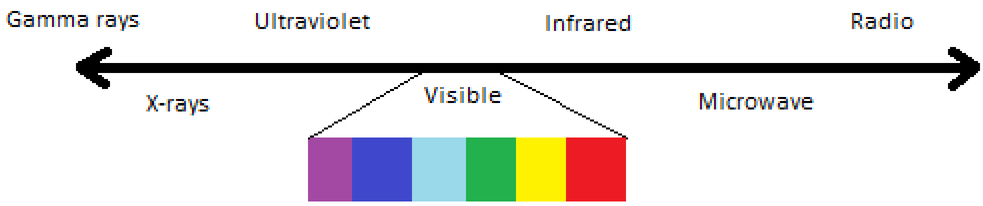


Figure 4: The colors in the visible spectrum.

Molecules can schematically be represented by point masses with springs between them as seen in Figure 5 and if each point mass is to be described by its position in space, at least three components are needed to describe each point mass, for example its x, y and z coordinates. If the molecule consists of N point masses, 3N variables are needed to describe the whole molecule's positions because every point mass needs its own x, y and z coordinates. The molecule thus has 3N degrees of freedom.

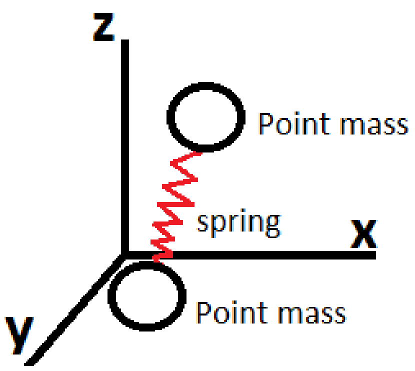


Figure 5: One molecule consisting of two point masses and the schematically painted spring between them.

For molecules with more than two point masses, there are only 3N-6 modes for nonlinear molecules and 3N-5 modes for linear molecules. This is because the space coordinates are only interesting relative to the other point masses. The linear molecules has one less vibrational mode because rotation around its own axis is impossible to observe. A molecule consisting of two point masses (N=2) will have 3N = 6 degrees of freedom. Each point mass can only move in its x, y and z coordinates and with two point masses, it will be six possible position changes.

Whenever there is a change in a molecules vibrational or rotational movement, infrared radiation is emitted. Because only molecules that are absolutely 0 K are completely still, every molecule above 0 K will emit infrared radiation. Infrared radiation is divided into a few categories, depending on the wavelength of the radiation (Table 1). The regions are not exact defined and Table 1 provides an approximate definition.

Region (abbreviation)	*Wavelength in µm*
Near infrared (NIR)	0.78-1
Short wavelength IR (SWIR)	1-3
Medium wavelength IR (MWIR)	3-6
Long wavelength IR (LWIR)	6-15
Very long wavelength IR (VLWIR)	15-30
Far infrared (FIR)	30-100
Sub millimeter (SubMM)	100-1000

Table 1: The different regions of infrared radiation. (Rogalski, 2010)

IR cameras usually operates in the LWIR. Because in this region, it is possible to construct a complete image of the surrounding temperature where the temperature differences are small such as room environment. The near infrared region (NIR) has its name because of its proximity to the visual spectrum. (Colthup, Daly & Wiberley, 1990)

2.2.1 Black body and emissivity

An important concept in thermography is the concept of a black body. A black body is an idealized object, not existing in its true form anywhere in the universe, the closest being a black hole. A black hole absorbs all radiation because of its immense gravity and it let no light escape. A black hole is however a source of some radiation, this is because the events that are creating this radiation is taking place at just the right distance from a black hole, near the so called event horizon. The net effect of a black hole will thus be that it absorbs all radiation that it is bombarded with but still emits radiation, which is based on its temperature. (Hawking, 2009)

So what is so special about a black body, if it doesn't even exist? The answer to that question is that scientist and engineers can pretend that black bodies exist and then give these black bodies the following properties:

- It should absorb all incoming radiation.
- Its temperature should be constant if it is in thermal equilibrium.
- All its emitting energy comes from its molecular vibrations, also known as the temperature.

The higher temperature a black body has, the more radiation it will emit, not just at some frequency, but at all frequencies with a peak in intensity at a specific frequency. As the temperature of a black body increases, the peak intensity will be larger and be shifted towards higher frequencies (Figure 6). Higher frequency means shorter wavelength, hence hotter objects will emit radiation with shorter wavelengths. A black body absorbs all the energy coming towards it, it will reflect no radiation and let no radiation transmit through it. All the radiation that the black body absorbs will cause the black body to heat up and increase in temperature and increase the molecular vibrations. Objects that are close to being a true black body are as mentioned black holes, but also stars and light bulbs. Some objects can be very close to a black body in certain wavelength spans, for example is snow a good approximation of a black body in the infrared spectrum but obviously not so good in the visible spectrum because it appears white and thus reflects much of the light from its surroundings.

The radiated power from a black body, or more precisely the total energy radiated per unit surface area across all wavelengths per unit time (known as emissive power) is described by the Stefan Boltzmann law (Equation 1).

$$Emissive\ power\ =\ \sigma T^4$$

Equation 1

Where σ is the Stefan Boltzmann constant, $5.670373 \cdot 10^{-8}\ Js^{-1}m^{-2}K^{-4}$.

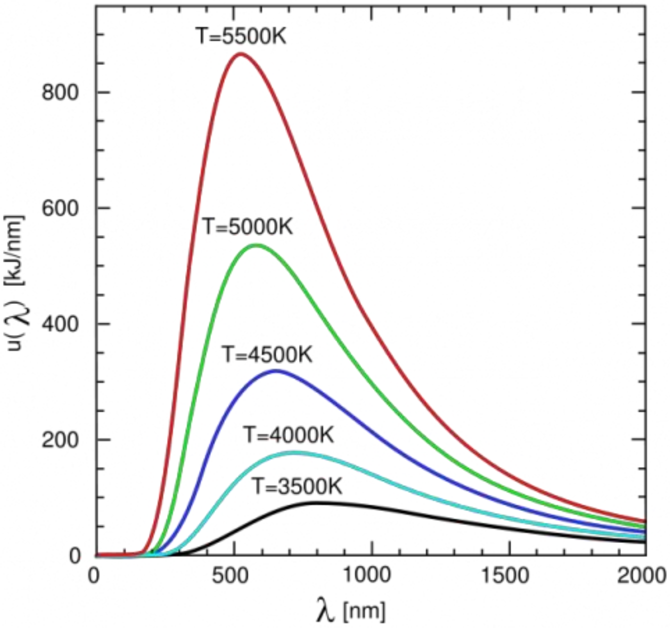


Figure 6: The distribution of different wavelength and their emissive power. The peak is shifted to the right with lower temperatures, indicated that as black bodies increase in temperature, their peak wavelength intensity will become shorter and shorter (more energetic). (Palma, 2014)

Figure 6 shows the distributions of the emissive power across the different wavelengths. The temperatures (expressed in K) in Figure 6 are relatively high but the curves have similar appearance with all temperatures above 0 K. (Colthup, Daly & Wiberley, 1990)

Emissivity is an object property very closely related to how good an object resemblances a black body. The emissivity is a ratio that can hold values from 0 to 1. If the emissivity is 1, then the object is a true black body. On the other hand, if it is close to 0, then the object may resemblance a shiny mirror more and is far from a black body. The emissivity of some materials can be seen in Table 2. The transmittance of an object is the fraction of how much radiation that passes through it, a transmittance of 1 means that the radiation passes through without any intensity degradation. The reflection describes how much radiation that an object reflects when radiation hits it. A value of 1 means that all the radiation is reflected (like a mirror). The emissivity, transmittance and reflection are connected by Equation 2.

$$1 = \tau + \rho + \varepsilon$$

Equation 2

Where τ is the transmission, ρ is the reflection and ε the emissivity. It is obvious that if the emissivity ε is 1, then τ and ρ must be zero and the object is a black body by definition. (Guyer, 1999)

Material	*Emissivity (ε)*
Aluminum foil	0.03
Ice	0.97
Asphalt	0.88
Polished silver	0.01
Brick	0.90

Table 2: Some example materials and their emissivity. (Brewster, 1992)

The emissivity is a setting that the IR camera user is able to set and change depending on the object the user is looking at. The temperature displayed in an IR camera is not always the true temperature of that specific object, it is an apparent temperature. This apparent temperature is calculated with some assumptions about emissivity. As the user is able to set the emissivity of the object that the user is looking at, the apparent temperature can sometimes show strange values if the emissivity is set to a poor value. If the emissivity is set to 1, the IR camera thinks that it is looking at a true black body, which often is a good enough approximation, but if this object is far from a black body (such as a shiny metal), the temperature reading will be very incorrect.

An example of a very poor black body is aluminum foil which has an emissivity of 0.03 and it probably has quite low transmittance, maybe even zero transmittance. The reflectivity of aluminum foil is most likely very high. Equation 2 showed the relationship between the transmittance, reflectivity and emissivity. If the reflectivity ρ is closer to 1 than 0 and the transmittance τ close to 0 the emissivity ε cannot be 1. But if the user has set the emissivity to 1, the calculations will be based on wrongfully assumptions and the apparent temperature will not correspond to real temperature values. With reflectivity above 0, the object will reflect infrared radiation from its surrounding which the camera will interpret as radiation originating from the shiny metal as it believes that the emissivity is 1.

2.3 Detectors

2.3.1 Photon and thermal detectors

There are two major types of detectors, photon detectors and thermal detectors. Photon detectors transmit the energy in the incident photons to electrons in the detector and thereby changes the electrical properties of the detectors. Thermal detectors absorb the thermal energy of the incident photons causing the detector to increase in temperature which alters the electrical properties of the detector. Changes in the electrical properties of the detector makes it possible to measure the properties of the photons causing this change. One commonly used thermal detector is the microbolometer that changes in resistance which is related to temperature. Microbolometers require no cooling which makes them popular in small handheld IR cameras. (Diakides, Bronzino & Peterson, 2012)

Photon detectors are divided into two categories, photoconductive and photovoltaic. The response in both these types of detectors when they are bombarded with photons is that the electrons in the detector are elevated to a conductive or free state.

Thermal detectors are generally able to operate in room temperature, in contrast to photon detectors which usually needs some kind of cooling to function properly. The temporal response (time from incident photon to detector signal) and detection capability is better on photon detectors compared to thermal detectors. They are on the other hand cheaper and therefore primarily used in handheld devices. The process taking place within a thermal detector is divided into two steps:

- Electromagnetic radiation is converted into heat in the detector. The photons are absorbed by the detector resulting in a temperature increase.
- The heat is converted into an electrical signal.

Because thermal detector in a sense only measures the temperature, it is wavelength independent and cannot distinguish between different wavelengths in the detected signal. Figure 7 shows the relative spectral response and the associated wavelength in the two detector types.

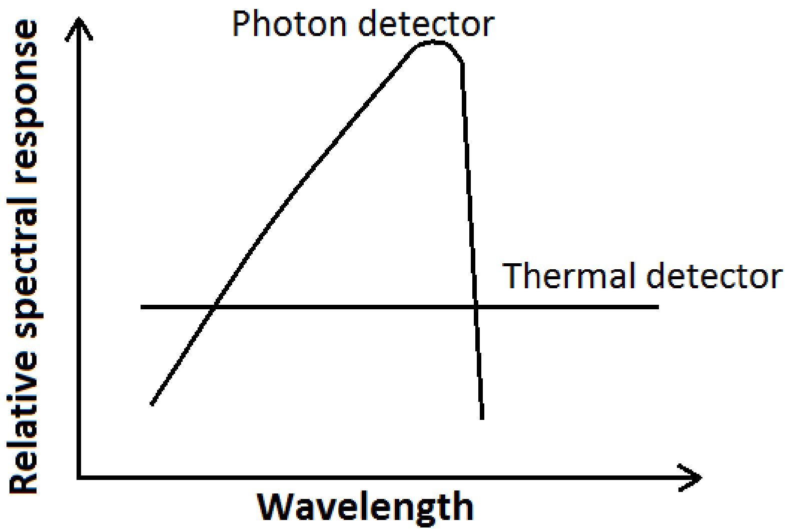


Figure 7: The sensitivity of photon and thermal detectors, the thermal detector is independent of the wavelength of the infrared radiation.

Thermal detectors can have a temperature resolution below 0.05 K. Temperature resolution is also known as NETD (Noise Equivalent Temperature Difference) which is the smallest temperature difference the detector is able to distinguish from the noise. (Vollmer & Möllmann, 2011)

2.3.2 Detector signal

The detector signal does not contain temperature data in degrees Celsius or degrees Kelvin, but rather the raw signal from the detector. It is not meaningful to display this signal directly to the user as the relation between the detector signal (S) and corresponding temperature (T) are not only different in every camera but also nonlinear and non-intuitive and presentation of this data would be pointless. The relation between the raw signal and temperature is given by Equation 3.

$$RBF(T) = f(S)$$

Equation 3

RBF is a function depending on the temperature and f(S) is a function that converts the detector signal to the 16 bit raw signal. T is the temperature and S is the signal from the detector. To convert the raw signal to a power signal (in Watts), the offset (J_0) has to be added and then multiply the signal with the gain (J_1).

$$Power\ in\ W = RBF(T) = f(S) = (S + J_0) * J_1$$

Equation 4

To extract the temperature from the RBF function, the parameters R, B and F are needed, and these vary between different cameras. The RBF function is given by Equation 5.

$$RBF(T) = \frac{R}{e^{\frac{B}{T}} - F} = (S + J_0) * J_1$$

Equation 5

The correct temperature is achieved by inverting the RBF function and compensating for the gain and offset. The resulting expression will be Equation 6.

$$T = \frac{B}{\ln\left(\frac{R}{(S + J_0) * J_1} + F\right)}$$

Equation 6

The resulting equation explains how to transform the 16 bit signal to correct temperature data in K. Notice that R, B, F, J_0 and J_1 are all constants and the only independent variable is S. Figure 8 shows the complete flow diagram.

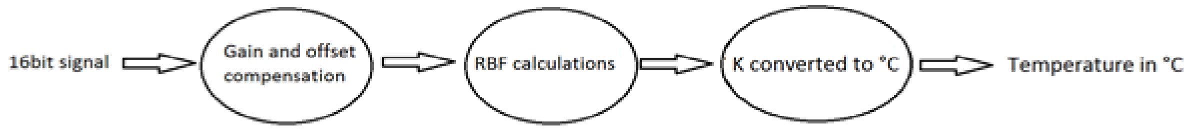


Figure 8: The complete flow of the signal, from 16bit to temperature in °C.

2.4 Filters

IR cameras at FLIR utilize bilateral filters to remove some of the noise and provide a better image. A bilateral filter is a non-linear filter which blurs an image while maintaining strong edges. When this filter is applied, each pixel is replaced by a weighted average of its neighboring pixel values. The size of the averaging pixel window and the contrast of the preserved features can be specified. The equation for filtering an image is described in Equation 7. (Paris, Kornprobst & Tumblin, 2009)

$$image_{filtered}(x) = \frac{1}{W} \sum_{x_i \in \Omega} I(x_i) f_r(\|image(x_i) - image(x)\|) g_s(\|x_i - x\|)$$

Equation 7

Variable	*Representing*
$\mathrm{image}_{\mathrm{filtered}}$	The filtered image
$image$	Input image to be filtered
f_r	Range kernel, usually a Gaussian
g_s	Spatial kernel, usually a Gaussian
x	Current pixel to filter
Ω	Pixel window surrounding x

Table 3: The variables included in the calculation of a smoothened image.

W is a normalizing factor, given by Equation 8.

$$W = f_r(\|image(x_i) - image(x)\|) g_s(\|x_i - x\|)$$

Equation 8

2.5 Colorization

2.5.1 Color spaces

Defining color may sound easy at first, the sun is yellow and the sky is blue but to describe colors in a less subjective way, a specific color model is needed, such as RGB, YCbCR, HSV or other. The three just mentioned are the ones used in this thesis.

2.5.1.1 RGB

The RGB color space is an additive color space consisting of the colors red, green and blue. This color space may be the most well-known, mostly because its resemblance to how the human eye works. Every pixel in a RGB image contains three values where each value tells how much of each of the color red, green and blue the pixel contains. The RGB values are often normalized between 0 and 1 to avoid confusion when talking about RGB images because images can have very different color depths. Frequently used color depths are 24 bit color depth, which means that each pixel is described with 24 bits. Divided on each color, every color gets 8 bit of data, meaning that the amount of red, green and blue can vary between 0 and 255. (Gillespy & Rowberg, 1994)

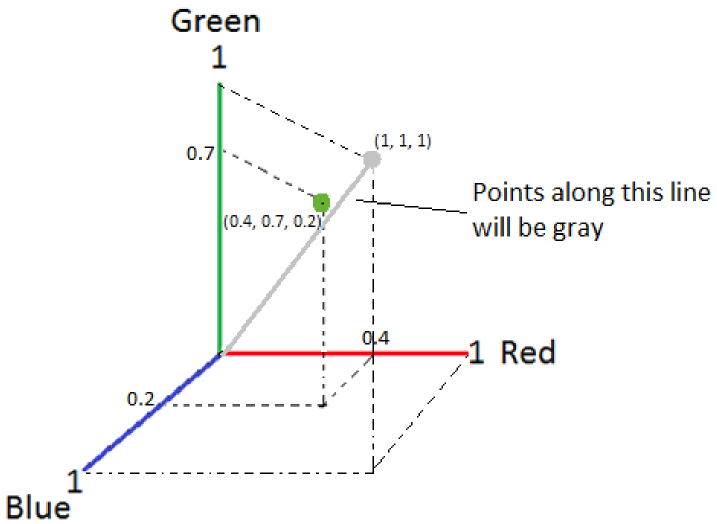


Figure 9: The RGB color space, notice the "gray line" going from (0, 0, 0) to (1, 1, 1) which represents gray pixels

Figure 9 shows the RGB color space where each pixel is a point in the RGB space. Note that (0, 0, 0) equals black and (1, 1, 1) equals white. A line drawn from (0, 0, 0) to (1, 1, 1) has the same amount of each color, this will result in a grayscale line starting at black going to white. Every pixel where R=G=B could be represented by a gray pixel with the value $\frac{R+G+B}{3}$ and because R=G=B, the grayscale value is any of the values. If the RGB values would not be the same, the previous equation is a transform from the three dimensional RGB space to the one dimensional grayscale space resulting in a grayscale image from a color RGB image. This transform just gives the average of the RGB values and may not be the best way to go from a color image to a grayscale image. (Plataniotis & Venetsanopoulos, 2000)

2.5.1.2 YCbCr

The YCbCr color space is a transformation of the RGB color space with an offset and a little smaller nominal range. The Y component, which represents the luminance of the pixel have a range of 0.0627 to 0.9217. The Cb component, representing the chrominance of the color blue have the range 0.0627 to 0.9412. The Cr component has the same range as the Cb component, but represent the chrominance of the color red. The YCbCr color model separates the luminance from the colors which makes this color model suitable for applications where it is necessary to remove the luminance influence on the colors. This could for example be very advantageous when developing face detection algorithms to detect faces in different lighting conditions. (Basilio *et al.*, 2011)

2.5.1.3 HSV

Hue, Saturation and Value are the parameters used to describe colors in the color space known as HSV. For clarity, the word brightness is used instead of the word value in this report. This color space is a little more intuitive and connected to how humans interpret colors. Normal people do not usually say that a wall has the RGB value (0, 0.3, 0.6), they would probably say something more similar to *"It is blue, feels quite saturated and not that bright"*. This is where the HSV color model is more suited, when humans describe colors and how they interpret them. Hue is nothing more than the true objective color perceived by humans. This could be red, green, orange or other. The hue can be any value between 0 and 360 and its appearance is shown in Figure 10. The hue values are red, orange, yellow, green, blue, violet and all the values between these colors, seen in Figure 10.

Figure 10: The different hues, which are represented by degrees, notice how it goes full circle and a hue of 0 is equal to a hue of 360. Hues are often normalized between 0 and 1.

The hue value is often normalized between 0 and 1. The hue scale is cyclic, meaning that the hue after 360 is 0. Saturation describes how much of white that is mixed into the color in the sense that a fully saturated color has no white in it. The saturation can be between 0 and 1 and the effect of different saturation on the hue red is seen in Figure 11.

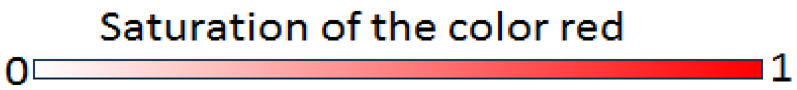


Figure 11: The color red, with an increase in saturation.

The last parameter in the HSV color model is the value, also known as brightness. The brightness is very similar to YCbCr's luminance, except that the brightness is separated from the hue, while luminance is depending much more on all the RGB values, the brightness only depends on the highest RGB value. The effect on changing the brightness on a fully saturated red color is seen in Figure 12.

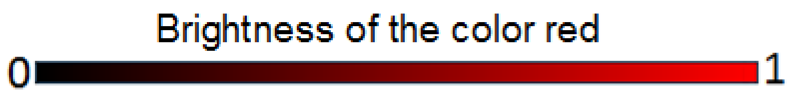


Figure 12: The color red, with an increase in brightness.

A grayscale image would have saturation at zero, a hue of any value and a brightness value that ranges from 0 and 1 where 0 is completely black and 1 is completely white. (Gonzalez & Woods, 2011)

2.5.2 Conversion between color spaces

It is of great value to be able to make calculations in one color space and then convert to another color space and perform other calculations in that color space because every color space has its own features that makes them favorable in different calculation situations.

2.5.2.1 RGB and YCbCr

The following conversion is used to convert a RGB pixel to the corresponding YCbCr pixel format.

$$\begin{bmatrix} Y \\ Cb \\ Cr \end{bmatrix} = \begin{bmatrix} 0.0627 \\ 0.5 \\ 0.5 \end{bmatrix} + \begin{bmatrix} 0.2568 & 0.5041 & 0.098 \\ -0.1482 & -0.291 & 0.4392 \\ 0.4392 & -0.3678 & -0.0715 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

Equation 9

The RGB value of white (1, 1, 1) would in the YCbCr color space be represented by (0.9217, 0.5, 0.5) and the RGB value of black (0, 0, 0) would in the YCbCr color space be (0.0627, 0.5, 0.5). A grayscale image is able to take all the values between black and white, and it is obvious that the luminance is the only component changing between the pixels in a grayscale image (Cb and Cr are the same in white and black, there is no gradient in Cb and Cr when going from white to black). From the formula, it is also seen that the green pixel value contributes more to the luminance than the red and blue pixel values. The value of blue is almost discarded (only 0.098 of blue, 0.2568 from red and 0.5041 from green). This is because the human eye is the most sensitive to the wavelengths around 550nm, which corresponds to green light. (Ge *et al.*, 2010)

To convert an YCbCr color back to the RGB color space (which may be necessary if one for example is working in Matlab where the image display function needs an RGB matrix to display an image) Equation 10 is used. If the image would be showed in a FLIR IR camera instead, the image display function works with YCbCr images and no conversion back is needed. (Basilio *et al.*, 2011)

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} 1.164 & 0 & 1.596 \\ 1.164 & -0.392 & -0.813 \\ 1.164 & 2.017 & 0 \end{bmatrix} \begin{bmatrix} Y - 0.0627 \\ Cb - 0.5 \\ Cr - 0.5 \end{bmatrix}$$

Equation 10

2.5.2.2 RGB and HSV

The conversion from RGB to HSV is a little more complex than the RGB to YCbCr conversion. The starting point is an RGB image of course. The procedure is described below.

1. Define:
   $M = \max(RGB)$
   $m = \min(RGB)$

Equation 11

2. $Brightness(V) = M$
   $Saturation(S) = 1 - \frac{m}{M}$

Equation 12

3. if G≥B: $Hue(H) = \cos^{-1}\left[\frac{R-0.5g-0.5B}{\sqrt{R^2+G^2+B^2-RG-RB-GB}}\right]$
   if B>G: $Hue(H) = 360 - \cos^{-1}\left[\frac{R-0.5G-0.5B}{\sqrt{R^2+G^2+B^2-RG-RB-GB}}\right]$

Equation 13

The hue values will be given in degrees in these equations. The conversion from HSV to RGB is given below.

Define:
$C = V * S$
$X = C * \left(1 - \left|\left(\frac{H}{60}\right)\%2 - 1\right|\right)$ where % equals the modulus operator
$m = V - C$

Equation 14

The RGB values are then calculated depending on the Hue interval.

Hue	*(R, G, B)*
0-60	(C+m, X+m, m)
60-120	(X+m, C+m, m)
120-180	(m, C+m, X+m)
180-240	(m, X+m, C+m)
240-300	(X+m, m, C+m)
300-360	(C+m, m, X+m)

Table 4: Different intervals of the hue will give different formulas to calculate the RGB value.

There can be some ambiguity when converting between RGB and HSV, for example, what is the Hue value of a black pixel? A black pixel is zero in all RGB values. When R=G=B=0, the denominator and numerator in Equation 12 will both be 0, resulting in 0/0, which is undefined. This can cause problems when converting an RGB image to HSV color space, manipulating the values and then transforming the image back to RGB. For example, a completely blue image (RGB = (0, 0, 1)) transformed to HSV color space will be (0.66, 1, 1), if one then lowers the saturation to 0 (HSV = (0.66, 0, 1)), a completely white image is created, if the image then is transformed back to RGB, the hue information is lost. Meaning that if it is converted back to HSV again, and increases the saturation to 1, then image would not know which Hue value it should have because the Hue value has been lost in the transformation between color spaces. (Burger & Burge, 2009)

2.5.3 Table of example colors

Some example colors below are expressed in RGB, YCbCr and HSV to give the reader a view of different color representations. The values are normalized between 0 and 1 and contains one significant digit.

Color	(R,G,B)	(Y,Cb,Cr)	(H,S,V)
Red	(1,0,0)	(0.3,0.4,0.9)	(0,1,1)
Green	(0,1,0)	(0.6,0.2,0.1)	(0.3,1,1)
Blue	(0,0,1)	(0.2,0.9,0.4)	(0.7,1,1)
Yellow	(1,1,0)	(0.8,0.1,0.6)	(0.2,1,1)
Cyan	(0,1,1)	(0.7,0,7,0,1)	(0.5,1,1)
Magenta	(1,0,1)	(0.4,0.8,0.9)	(0.8,1,1)

Table 5: Some example colors and their representation in different color spaces.

One sees in Table 5 that every color with much green in it receives a high value of the luminance in the YCbCr color space.

2.5.4 Indexed images

Indexed images are nothing more than a two dimensional array where each value in the array represent an intensity or some other representation of some real world phenomena. In IR images, this value is associated with the detector signal and contains information regarding the temperature of what the user is aiming the camera towards.

RGB images contain another dimension of data where each value do not just contain one value but three values, each representing the amount of the colors red, green and blue. An indexed image with a resolution of 480x640 pixels would only be an array with the size of 480x640, while an RGB image with the same resolution would have to be represented by an array of the size 480x640x3. An HSV image is much like a RGB image, except that instead of red, green and blue, each plane represents the hue, saturation and value (brightness). The same with YCbCr where each plane is the Luminance, blue chrominance and red chrominance.

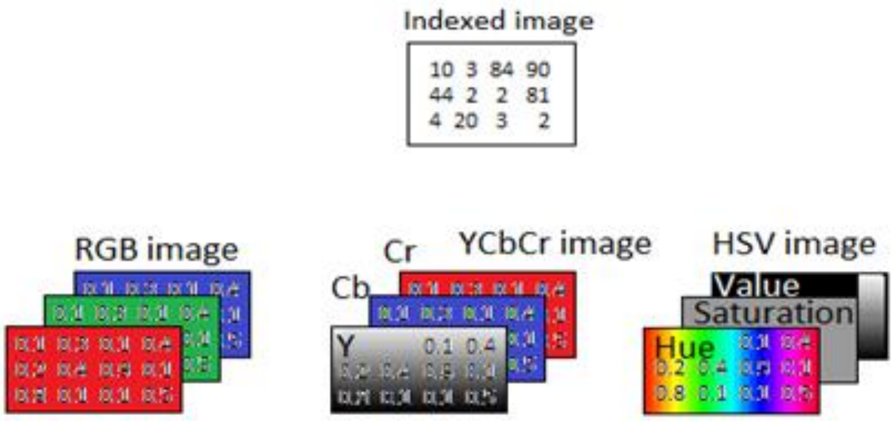


Figure 13: The difference between image types, notice how indexed image has one dimension less than the other three images.

Figure 13 displays the difference between an indexed image and an image with color. It is obvious that an indexed image is not really an image because if an indexed image is going to be displayed, it has to be mapped to some kind of look up table containing colors, or else it is just numbers.

2.5.5 Palettes

A palette is a look up table used to colorize indexed images. The look up table consists of a finite number of colors that are available to the colorization of pixels depending on their value. A palette can also be referred to as a color map. The palette transforms an image that contains no colors to an image containing *pseudo colors*. They are called pseudo colors because the colors are not real in the sense that the colors comes from some natural phenomena producing this exact color or that exact color, the colors are just what the palette distributes to the pixels. The color column in the look up table can be described in any color space. Matlab presents images with different image presentation functions, all these functions take as argument an RGB matrix. This means that if an image is manipulated in HSV color space, it has to be converted to RGB color space before the Matlab image presentation functions is used.

Intensity value	***Color***
0	black
1	blue
2	green
3	red
4	yellow
5	white

Table 6: Example palette/look up table.

Table 6 shows an example palette where the intensity values 0 will be colorized in black, intensity values 1 will be blue etc. The colorization of some intensity values are seen in Figure 14. It is only relevant to talk about palettes when dealing with indexed images and not when dealing with RGB/HSV/YCbCr images because they alreade contain color information. Palettes and look up tables are used to map a certain intensity value (from the indexed image) to the value in the palette which often contain RGB values or other representation of colors (HSV for example). So the result of an indexed image that has been colorized with a palette is a three dimensional matrix with RGB values.

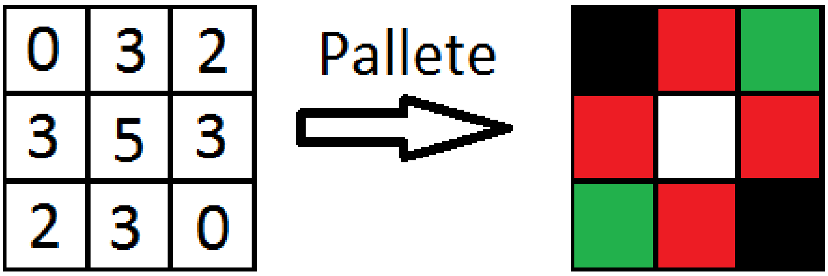


Figure 14: Indexed image colorized with the example palette.

Figure 14 shows the resulting image after applying the palette in Table 6 to an indexed image. If a pixel value of 999 would exist in the indexed image in Figure 14, it would be saturated in the palette and colorized as white.

2.5.6 Palettes in use today

There are numerous palettes available today in thermal cameras and it would be pointless to go through them all but the most popular are explained in brief. The most popular palettes are seen in Figure 15.

Iron palette is a palette where the hottest pixels in the image is white and the coldest are bluish , this is one of the most popular palettes. Rainbow palette uses more colors than the iron palette and represents hot pixels with white and cold pixels with blue and the pixels in between are represented by the colors of the rainbow. The rainbow palette also resembles how the visible region in the electromagnetic spectrum looks like.

A grayscale palette colorizes an indexed image in grayscale colors. A property that grayscale images has is that in a pixel, every RGB value is the same, red = green = blue that is.

Which implies that a grayscale image is some kind of hybrid between an indexed image and a color image. Because an indexed image contains enough information to colorize it in grayscale and no palette is actually needed.

Then there are two related palettes, one which colorize all pixels above a certain value and another palette that colorize all pixels below a certain cutoff value/temperature. It is up to the user to decide which palette to use and different cameras contains different palettes.

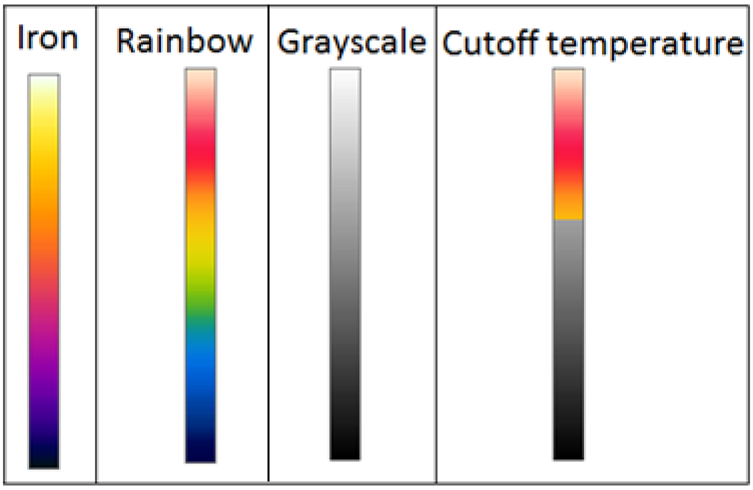


Figure 15: The most used palettes today.

2.6 Human visual system

To understand how the brain considers something to be intuitive, it is necessary to understand how the human visual perception system works. The first frontier where light interacts with the visual system is on the cornea, pupil and lens where the light is refracted and then projected as an inverted image on the retina. It is on the retina where the light has its first contact with the central nervous system (CNS) where there are photoreceptor cells (specialized type of neuron) that interact with the incident photons. The refraction taking place in the cornea, pupil and lens is the largest in the cornea. This can be tested by opening the eyes when under water. Now the eye is surrounded by water on the outside and as the cornea consists mostly of water, there will be almost no refraction taking place at the water/cornea interface. This will result in a blurry vision as the effect of the cornea is now removed and only the pupil and lens are used to focus the light to the retina. The lens is however able to change its refraction to give focus to object that is at different distances. (Purves, 2007)

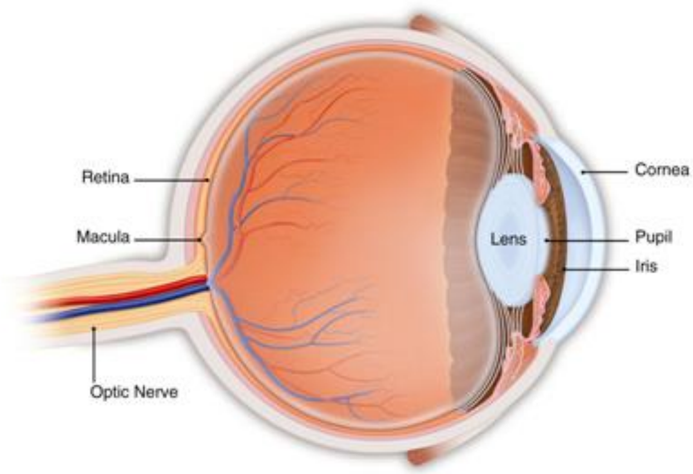


Figure 16: The human eye.(Http://2020aec.Com/Wp-Content/Uploads/2011/04/Anatomy_Eye.Jpg, 2004)

The photoreceptor cells at the retina contain certain proteins that are specialized in absorbing photons and creating a change in the photoreceptor cells membrane potential causing an electrical potential to spread to other neurons. The two big groups of photoreceptor cells are the cones and rods. Rods are much more sensitive to light than the cones and have the ability to detect as few as just six photons, they however, do not respond to color. The ability to see colors comes from the cones which is responsible for the color vision. There are three different kind of cones, each responsible for a wavelength span, the short, medium and long wavelength cones and they vary in numbers. The short wavelength cones only makes about 5-10 % of the total number of cones while the medium and long wavelength cones ratio is different on all humans. Figure 17 shows the cones sensitivity to different wavelengths. A cause of color blindness could be that there is a problem with the sensitivity of the cones to different wavelengths. Once the cones and rods has done their job, the signal goes to the brain for further processing. (Hecht, Shlaer & Henri Pirenne, 1942)

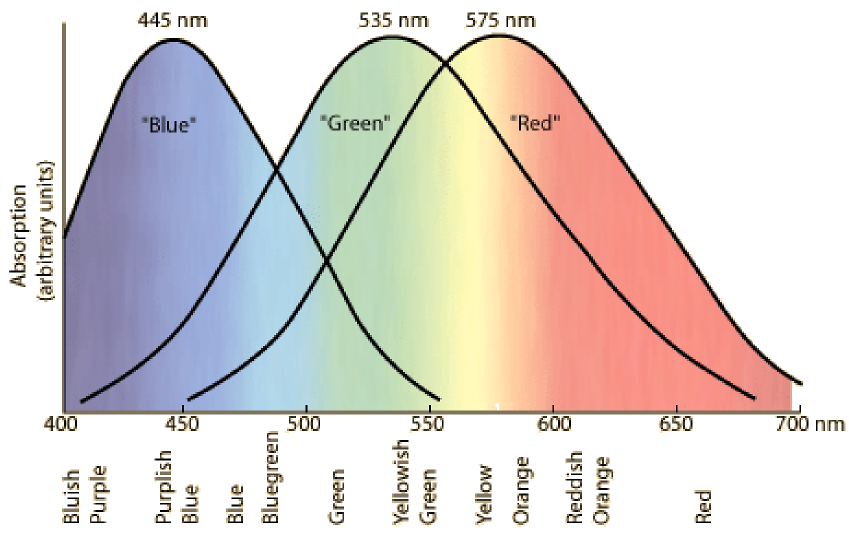


Figure 17: The cones sensitivity to different wavelengths of lights. (Http://Hyperphysics.Phy-Astr.Gsu.Edu/Hbase/Vision/Imgvis/Colcon.Gif)

As explained earlier, the cones are responsible for human's ability to see colors and compare two colors to each other and say that one color is orange and the other is yellow. To be able to do this, the brain has to be able to compare the input from one type of cones to another type of cones. Exactly how the brain do this is still unclear. (Purves, 2007) The visual perception is very dependent on the context of what one is looking at. The factors affecting human perception of objects are length, area, orientation and brightness. Figure 18 shows how the squares A and B appear to have different colors but they have in fact the same color.

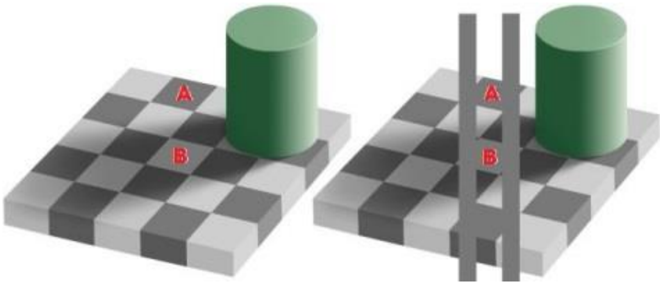


Figure 18: The same color appears to change because of a change in its surrounding. (Http://I1-News.Softpedia-Static.Com)

How humans see contrast, also known as difference in brightness, is depending on the firing rate in the photoreceptor cells in the retina. But as mentioned, how the contrast is perceived is heavily affected by its context as Figure 18 shows. The term describing this is known as lateral inhibition which is a phenomenon when one neuron's activity affects its neighboring neuron activity. Lateral inhibition is not bound to the neurons in the retina but is present on multiple places in the human body, for example on the skin. When you stick a sharp object on to your skin (don't do that), there will be many neurons affected but the neurons closest to the object will create the strongest response which will in turn inhibit the surrounding neurons making it easier to localize the sharp object. It works the same way in the retina where lateral inhibitions makes it easier to see contrast differences. (Sherwood, 2010)

To describe how small contrast difference humans can see, the concept of the unit *Just Noticeable Difference* (JND) is used. The JND is defined as the luminance difference under some viewing condition that makes the average observer distinguish a difference in luminance. There has to be at least 1 JND between two gray levels in an image if a person should be able to see the difference between these two gray levels. (Todorović, 2010)

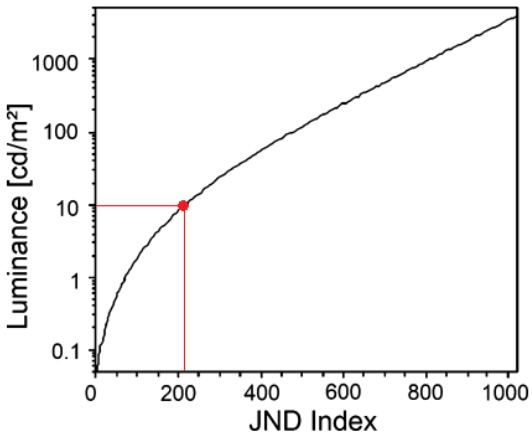


Figure 19: The luminance as a function of the JND index.

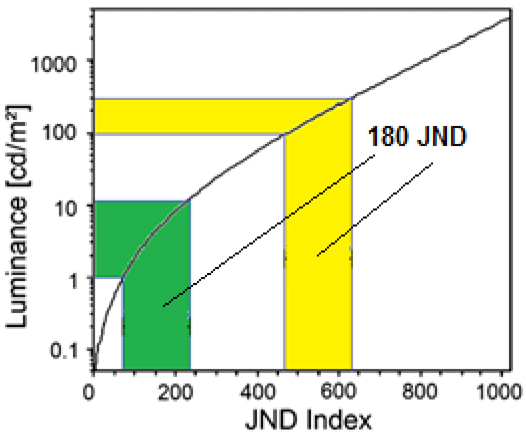


Figure 20: Showing how different luminance contains a different amount of JNDs.

Figure 19 displays the luminance and JND index. In the range of 0 to 10 in luminance (expressed as candela per square meter) there are approximately 210 JND, which means that the average observer will be able to distinguish between 210 different gray levels in this luminance span. The number of JND in a given luminance span is not linear and this is shown in Figure 20 where the same number of JND (180) gives the same perceived contrast but completely different luminance differences (1-11 vs 100-300).

One can draw the conclusion that humans are more sensitive to luminance differences in dark areas than in bright areas. In the green area (Figure 20) there are 180 JND in the interval of 1 to 11 in luminance while in the yellow area the luminance goes from 100 to 300, also with 180 JND. As both these areas contains the same amount of JND it is easier to see luminance differences in dark areas because there are more JND per luminance in darker areas. (Kimpe & Tuytschaever, 2007)

2.6.1 Intuitive colorization

The goal of this master thesis is to colorize infrared images in an intuitive manner. The definition of something that is intuitive according to the Oxford Learners Dictionaries is something that is:

"..obtained by using your feelings rather than by considering the facts."

This definition is the basis of this master thesis and the goal is to have an intuitive colorization of IR images that gives the user a good idea of what is shown based on his or hers feelings rather than a perfect representation of IR radiation, camera structure and material properties. Even with the quite clear definition of what something should be if it should be categorized as intuitive, it could be difficult to create something that is intuitive. The colors representing certain temperatures must give the user a feeling of that specific temperature.

2.6.2 Brightness/Lightness constancy

Brightness or lightness constancy is a term describing how humans perceive the brightness of objects in different lighting conditions but still see an object as for example white. A completely white paper outside on a bright sunny day will appear white. Looking at the same paper in a dark basement, it will also be white even though the external illumination has changed. The same goes for a green paper (or any other color), it would look bright green outside and dark green in the basement, but it would look green in both situations. A human would describe the paper as green in both circumstances, but a computer would have problems with recognizing the two different scenarios as having the same paper color. (Maloney & Wandell, 1986)

If an object is moved between a light area to a darker area, it will not appear to be changing much in color (as long as the dark area has some illumination at least), this is the work of the brain trying its best to understand that the object is the same object even if it appears to change as the illumination changes. The image that a person thinks she is seeing is a product of what the eyes see and how the brain interpret this information. This is why it is hard for a computer to recognize this object as the same object, the computer only has eyes (detectors) in a sense and how the human brain interpret this information is difficult to mimic in a computer. (Zettl, 2013)

2.6.2.1 Hot and cold colors

Different colors can influence how people feel temperatures. A study was performed where one room was painted in a blue-green color and another in red-orange. The temperature was then decreased until the occupants in the room said that they felt cold. In the blue-green room people started feeling cold at 15 °C, in the red-orange room it was not until the temperature reached 11-12 °C that the occupants started to complain. One can draw the conclusion that "warm colors" even increases the blood circulation and "cold colors" decrease the circulation. (Itten & Birren, 1970)

The general theory is that red equals hot and blue equals cold, but it may be a little more complex than that. Some red colors can appear cold and some blue colors can feel warm. One theory is that it is not the main hue that determines how a color feels, but rather the secondary hue. For example, a completely blue hue feels cold, but mix in a little red and the color will feel much warmer, same with red, mix in a little blue and it will appear much colder. (Wolfrom, 1992)

Another study showed that when test subjects touched a red or blue object, their estimate of the temperature was higher for blue object and lower for red object. Which in a way contradicts the study mentioned earlier. If a red wall has the temperature of 22 °C, a person touching it would according to the study estimate its temperature to be below 22 °C. If it was blue, the person would estimate it to be warmer than 22 °C. An explanation to this can be that red objects is believed to be hot and when a person actually touches a red object, it feels colder than it actually is because of the persons expectations. In a sense, this supports the general theory of red symbolizing hot and blue symbolizing cold. (Ho et al., 2014)

Blue light has higher energy than red light because blue light has shorter wavelength than red light, this also contradicts the general theory about red and blue a little bit. If one would look up to the sky and measure the temperatures of stars, one would see that red starts are actually colder than blue stars, this also goes against the idea of red equals hot and blue equals cold. All in all, it is difficult to assign colors to certain temperatures and expect it to be intuitive for everyone. (Chandler, 2015)

3 Phase 1: generic approach to achieve temperature/color constancy

This thesis work is divided into two phases. Chapter 3 describes the first phase where the goal is to achieve temperature to color constancy in a generic way. That is, to create a colorization of thermal data that can be used for any type of application. Chapter 4 describes the second phase, with a more specific approach where the colorization is constructed to fulfill the needs of a more application specific solution.

3.1 Method

The purpose of this master thesis is to identify intuitive ways of colorizing thermal data. Specifically achieving perceived color constancy of temperatures to the thermal camera user. To succeed with this, an iterative approach has been chosen with Matlab prototyping with the setup constructed as seen in Figure 21. Several different concepts were created on ideas generated from web research and workshops.

3.1.1 Equipment

The streaming signal from the IR camera to a computer is a 16 bit data stream and as the resolution of the camera is 640 pixels wide and 480 pixels high, each image contains 16*640*480 = 4915200 bits, equal to 614400 bytes, which is 0.6144 megabytes. The A615 camera which is used in this thesis has a frame rate of 60 Hz, meaning that the information that is sent from the camera through the Ethernet cable is 36.864 megabytes per second. The calculations taking place in Matlab result in a drop of frame rate. If or when the concepts from this thesis takes the step from Matlab implementation to being programmed into handheld IR cameras, the camera will probably be able to perform the calculations much faster.

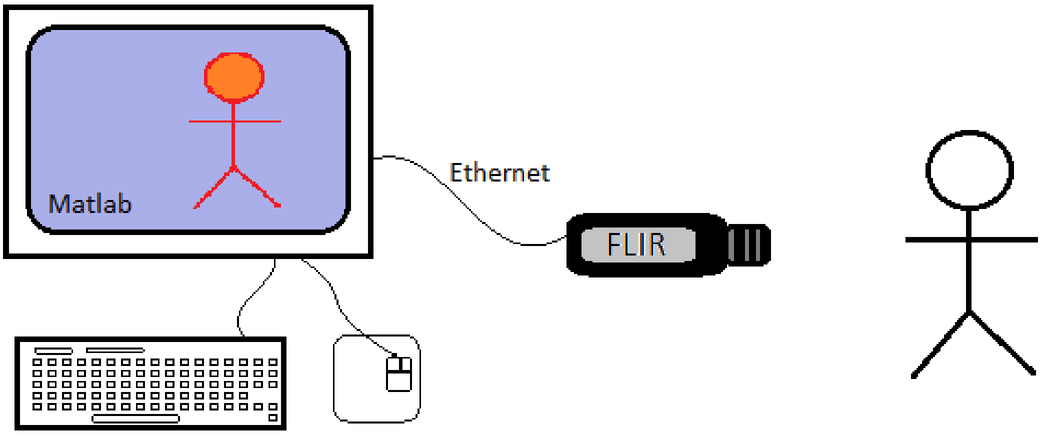


Figure 21: The experimental setup.

For the specific camera used in this master thesis, the R, B, F, J_0 and J_1 parameters had the values seen in Table 7. Recall from the theoretical background that these parameters are camera parameters that are different for each camera and are used to calculate the real temperature of objects from the streaming camera signal.

Camera Parameters	*Values*
R	16688
B	1430
F	1
J_0	-4139
J_1	0.0144

Table 7: Camera parameters for the specific camera used in this master thesis, a FLIR A615.

With the correct values connected with this specific camera model, the RBF equation becomes:

$$T = \frac{B}{\ln\left(\frac{R}{(S+J_0)*J_1}+F\right)} = \frac{1430}{\ln\left(\frac{16688}{(S-4139)*0.0144}+1\right)} = \frac{1430}{\ln\left(\frac{1158900}{S-4139}+1\right)}$$

Equation 15

Where T is in Kelvin and S is the 16bit signal ranging from 0 to 65535 (2^{16}-1). Please note that this equation is only valid for the specific IR camera used in this master thesis and is not to be used with other IR cameras. It is seen from the equation that signal values of 4139 will cause some undefined behavior because the denominator will be zero. S values below 4139 will result in a complex temperature value. This means that the signal span is a little smaller than 16bits because only values between 4139 and 2^{16}-1 will give meaningful temperatures. The detector signal from the camera used in this thesis is plotted as a function of temperature in Figure 22.

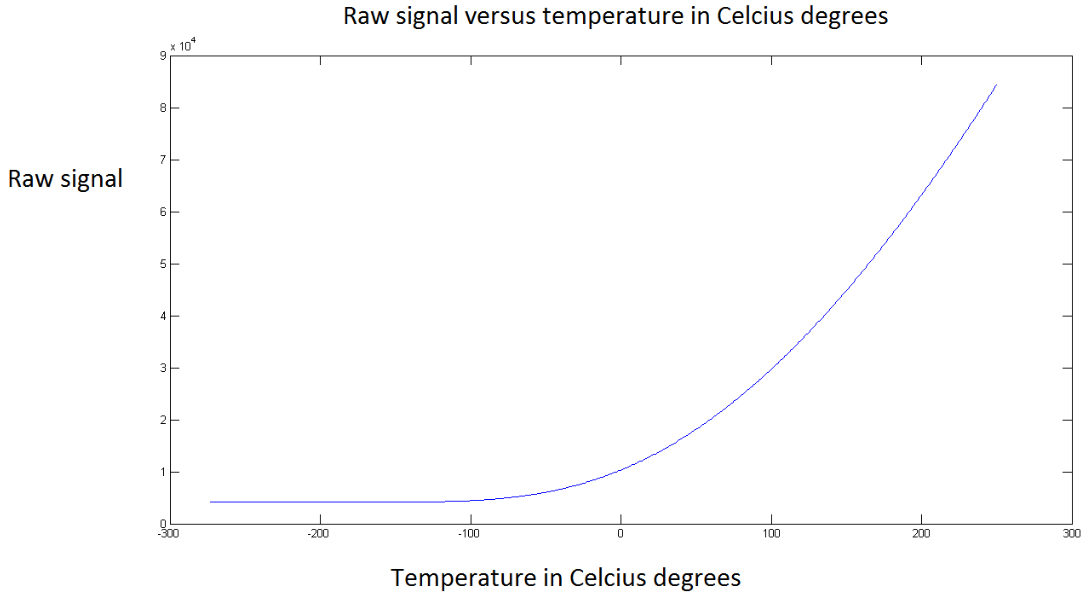


Figure 22: The specific camera used in this master thesis has this temperature curve showing how the sensitivity is very low below -40 °C and almost linear in the camera temperature range which is -40 °C to 150 °C.

To compare between the different concepts, a set of reference images were constructed. The first test image is a scene containing a cup with cold water, a cup with hot water, a black body radiator (device that can be set to high temperatures) and a damp stain on a wall. The test image has to be able to test if the concepts fulfill the goals proclaimed in the introduction which in brief was:

1. Specific colors/hues should be fixed to specific temperatures.
2. The contrast should be comparable to the contrast in the use today.
3. The images should be intuitive.

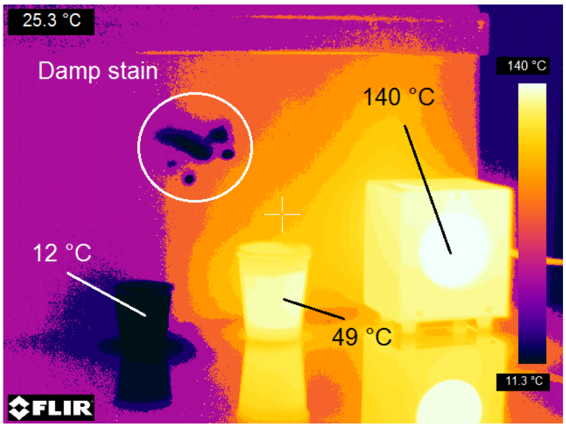


Figure 23: The iron palette reference image with a large temperature span.

Figure 24: The iron palette reference image of an outside environment.

Figure 23 shows the first test setup with different object with relatively large temperature differences. The palette seen here is the iron palette which is the most used today. The coldest object is the cup at 12 °C and the hottest is the black body radiator at 140 °C. The second test image (Figure 24) shows a car outside on a parking lot, with the camera aimed towards the car from above. This image is included to test the colorization on an outside environment.

3.2 Procedure: concept development

All concepts in phase 1 are based on the same colors in the same order. From blue being the coldest, via green, yellow and orange to red as the hottest. But the way it is combined with grayscale information differs. This base palette is constructed to contain sufficient amount of colors in the camera temperature range and give an intuitive colorization of temperatures. The palette is created to be used by humans and is there for custom fitted to give good contrast in temperatures where humans often spend time. The palette is constructed with the feeling of warm and cold colors in mind aiming to really give the user a sense of objects temperature just by looking at the color. Using only this palette would not give sufficient contrast as can be seen in Figure 25. If Figure 23 is compared to Figure 25, it is seen that the contrast is much better in Figure 23. This is because the iron palette do not have fixed color to temperature, and hence can use all its colors within the current temperature span. The following concept uses different ways to increase the contrast with this palette (the one used in Figure 25) while maintaining the color to temperature matching.

Figure 25: Stretching the palette to the temperature range of the camera result in low contrast but constant color to temperature matching.

The saturation of this color to temperature constant palette is set to 1 to give bright and saturated colors. In Figure 25, the brightness of the palette is also set to 1. The colors in the palette are not constant over the color range, for example in the yellow region of the palette, there is a gradient from yellow (RGB = (1, 1, 0)) to orange (RGB = (1, 100/255, 20/255)). The code for generating the palettes are included in appendix A.

3.2.1 Concept 1: fixed colors and dynamic grayscale

The first concept is based on the idea that maximum contrast is achieved if the full spectrum of available colors is used to colorize an image. For example, if all the pixels in an image (indexed image) is in the span of 0 to 5, it will be terrible contrast if a palette that goes from 0 to 100 is used, but if a palette is altered to only range between 0 and 5, the contrast will be much better. Figure 26 displays the effect of having a too large span on the palette compared to the actual pixel values. The contrast is much better in Figure 27.

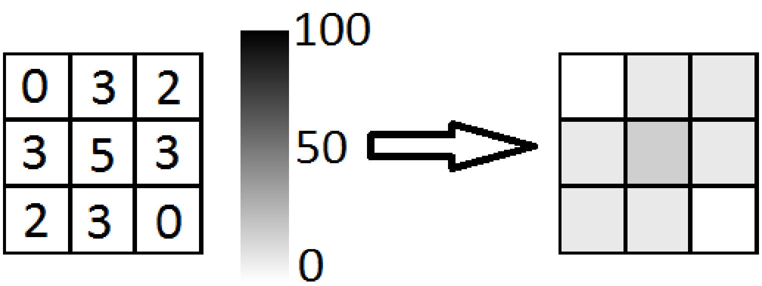


Figure 26: Grayscale palette and the effect of having a too large span in the palette, which will result in low contrast.

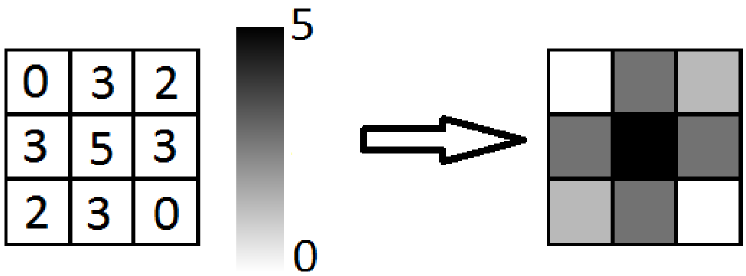


Figure 27: Grayscale palette with smaller span more fitted to the specific image, which will result in much better contrast.

The first step in concept 1 is to create this maximum contrast image by letting the palette maximum value correspond to the image maximum value and the same with the minimum value. It is obvious that this palette would not give absolute color to temperature matching because the representation of each pixel is depending on all the other values in the current scene. The problem with relative colorization is still existing here, where good contrast is achieved at the cost of having no connection of temperature to color (remember the figure of the computer mouse in the theoretical background, Figure 1). The major advantage of this maximum contrast image is of course the good contrast. The palette adapt itself to the current span in the scene.

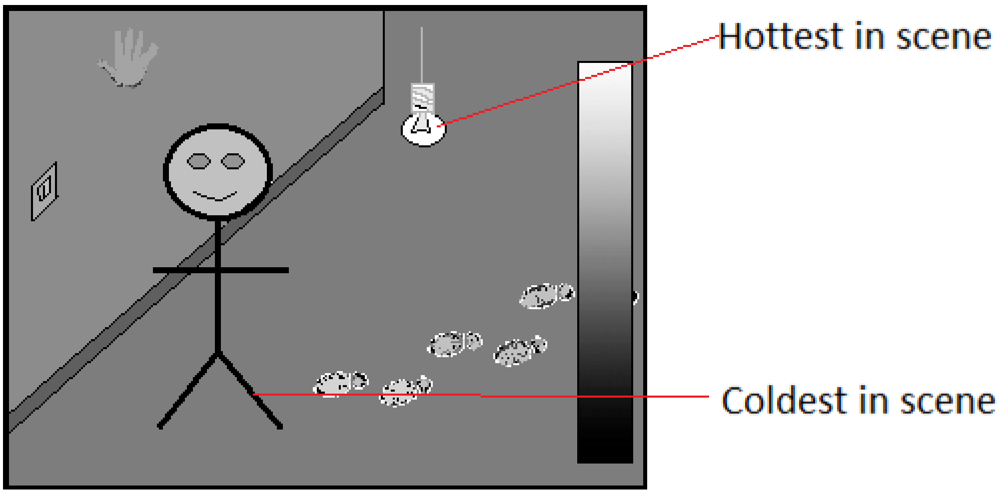


Figure 28: Grayscale image with good contrast where small details are visible, the grayscale adapts itself to the current temperature span in the scene.

Figure 28 shows the maximum contrast image where details are seen such as the footprints, light switch on the wall, filament in the light bulb and facial expressions. This image is colorized in a grayscale palette and this image will in the future be referred to as the grayscale image when describing concept 1. The pixels with the highest temperature will be colorized in white and the coldest in almost black. It will not go all the way to black, because it is needed later that the grayscale image contains no completely black pixels.

The values in each pixel has no direct connection to some specific temperature, they are all just given values depending on all the other pixels in the scene. To make the connection between pixel value and temperature, a color palette is introduced. This color palette can be as simple as the palette in Figure 29. Note that this palette in Figure 29 is only used to demonstrate the concept and not the palette used in the final solution. The difference with this palette compared to the grayscale palette used in Figure 28 is that the color is locked to temperature and is not changing depending on the current temperature span. If temperature in the scene would be above 100 °C, they would be colorized in red and temperatures below 0 °C would be light blue.

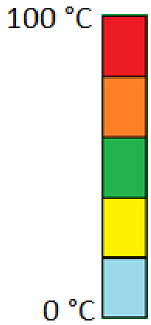


Figure 29: Palette locked to temperature, in this case 0 °C to 100 °C.

If this palette would be mapped to the image in Figure 30, the following image would be produced (schematically):

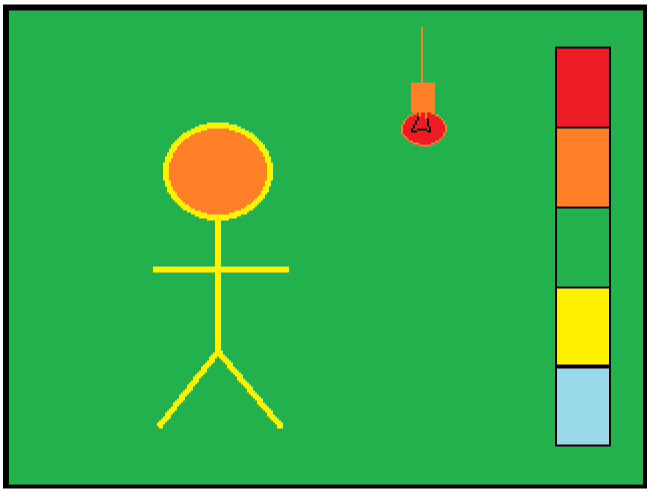


Figure 30: Color palette which is locked to absolute temperature, the blue color is not used because it falls below the temperature in the scene.

Figure 30 gives color that is connected to temperature, but the details are not there. This is because the details are lost when a palette with large temperature range is used, the small details are too small to be noticed by the palette which takes into account the whole temperature range and not just the span in this specific scene. Only temperature differences that is big enough to receive a significant different color by the palette is visible to the user. The point of locking the palette to such a large temperature span is to ensure that the camera is able to represent all the temperatures in the camera's temperature range. It is easy to see the difference between green and orange objects because their temperature difference is large enough. But objects with similar temperature that is colorized with almost the same color will be hard to see because of the low contrast in the image.

But what will happen when combining the grayscale image showing small details with the color image with true temperature to color mapping? The answer is hopefully something looking like Figure 31.

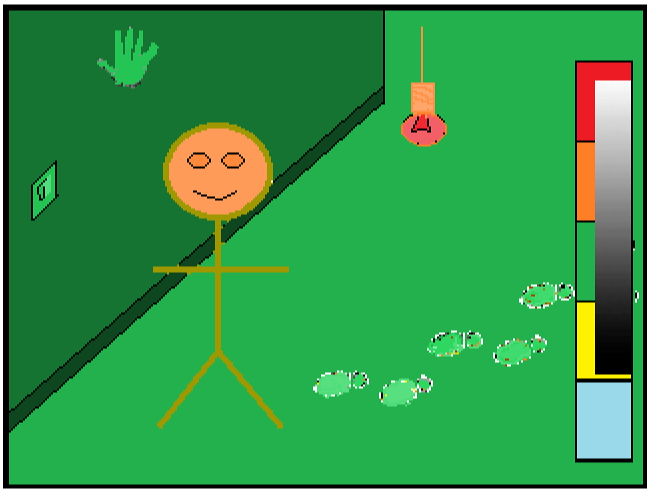


Figure 31: Contrast from Figure 28 combined with color information from Figure 30 will hopefully result in an image looking like this.

The resulting image (Figure 31) contains the details but also the temperature to color mapping. The question is how these two images should be combined. In this thesis, there are three methods described how to combine these two images. Roughly these methods work in different color spaces, where the first approach is carried out in the RGB color space, the second one in the YCbCr color space and the third one in the HSV color space. The conceptual idea of concept 1 is shown in Figure 32, where the grayscale is only applied in the temperature span that is in the current scene.

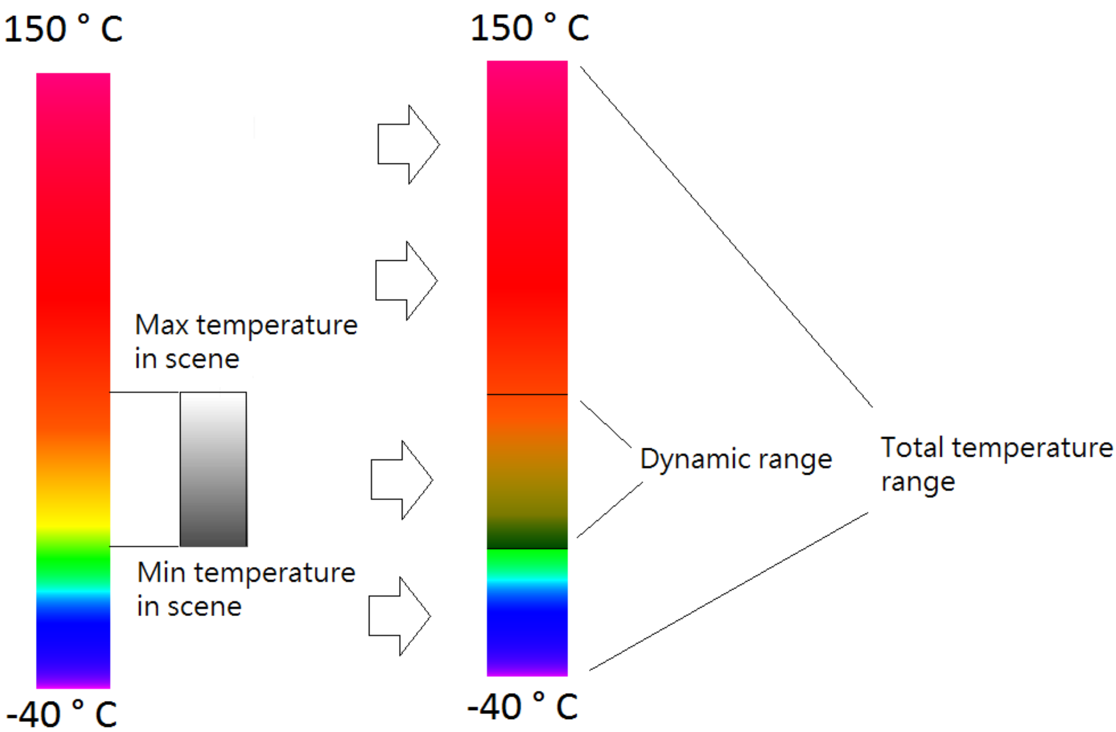


Figure 32: The color palette locked to the camera temperature range combined with the adaptive grayscale produces a new adaptive palette with constant color to temperature matching.

If the grayscale image would contain completely black pixels, these pixels would remove all color content in the combined image. Therefore, the grayscale is only allowed to have values between 0.3 and 1. For the evaluation, a solution with the grayscale ranging from 0 to 1 is also included to test how the user experience it compared to the version with grayscale between 0.3 and 1.

3.2.1.1 Concept 1: alpha blending

The first way to mix temperature fixed colors with dynamic grayscale information is by using what is known as alpha blending. Alpha blending is a method of adding two images together with the idea that one of the images is transparent to some degree. This is a common technique in computer graphics when combining a real life photography with some computer generated image. To perform this procedure, one must first assign an alpha value to each pixel, each pixel is represented by R, G, B and α values. The α-values are stored in what is known as the alpha channel. The value of the alpha channel can vary between 0 and 1. The value of 1 means that this pixel is opaque and it only shows its RGB values. If the alpha channel is 0, this pixel is completely transparent and none of the RGB information is shown. In Figure 33, a completely white image (RGB = (1, 1, 1)) is combined with an image of a boat. If the white image has the α-value 0, then one will see straight through it and only see the sailing boat image. If the white image has the α-value of 1, one will only see the white image.

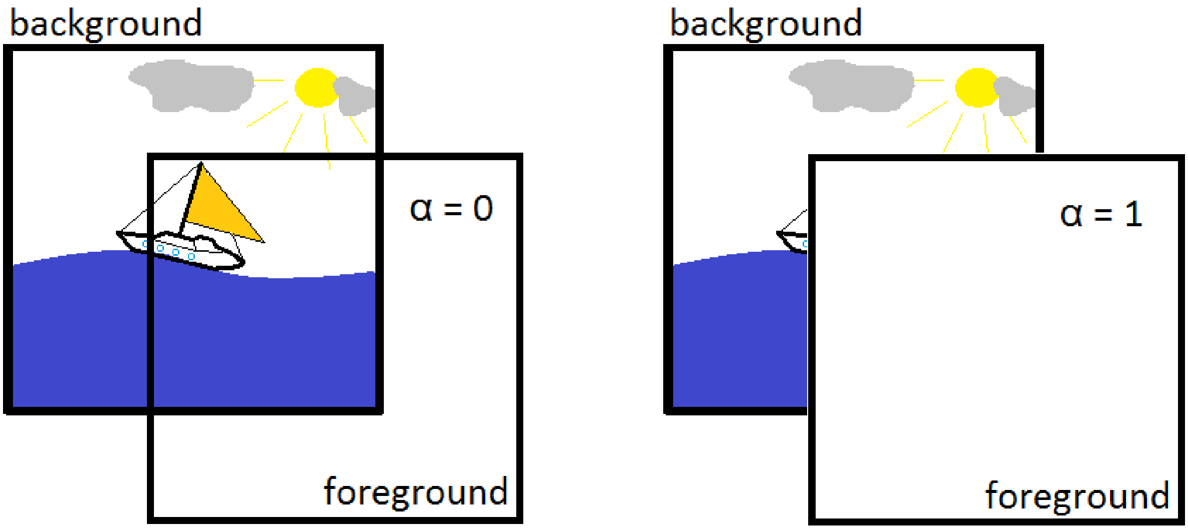


Figure 33: Image of a sailing boat alpha blended with a completely white image with two different alpha values.

The RGB values in the background image (in Figure 33, the sailing boat image) is affected in the following way:

$$RGB_{new\_background} = RGB_{old\_background} * (1 - \alpha) + RGB_{foreground} * \alpha$$

Equation 16

The water in the background image probably have an RGB value that is very close to completely blue, say (0, 0, 1) and the white image is still (1, 1, 1). The new RGB values in the background image will be (α = 0 in foreground):

$$R = 0 * 1 + 1 * 0 = 0$$

$$G = 0 * 1 + 1 * 0 = 0$$

$$B = 1 * 1 + 1 * 0 = 1$$

Equation 17

And when α = 1 in foreground:

$$R = 0 * 0 + 1 * 1 = 1$$
$$G = 0 * 0 + 1 * 1 = 1$$
$$B = 1 * 0 + 1 * 1 = 1$$

Equation 18

What would happen if α = 0.5 in the foreground?

$$R = 0 * 0.5 + 1 * 0.5 = 0.5$$
$$G = 0 * 0.5 + 1 * 0.5 = 0.5$$
$$B = 1 * 0.5 + 1 * 0.5 = 1$$

Equation 19

The resulting pixel would go from blue (0, 0, 1) to another blue pixel, but a blended version of its former self (0.5, 0.5, 1). See Figure 34

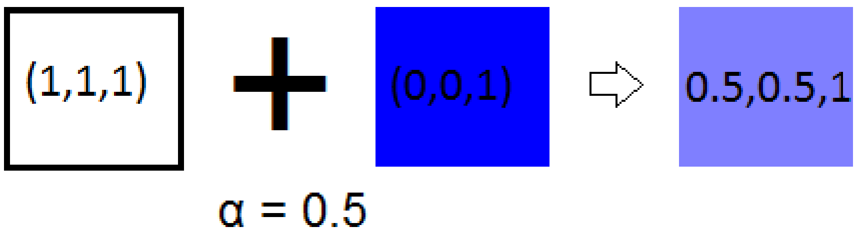


Figure 34: Alpha blending a blue pixel with a white pixel, with α equal to 0.5.

The sailing boat would appear as a blended version of itself when it is alpha blended with a white foreground (Figure 35). The resulting image is a form of average between the two images.

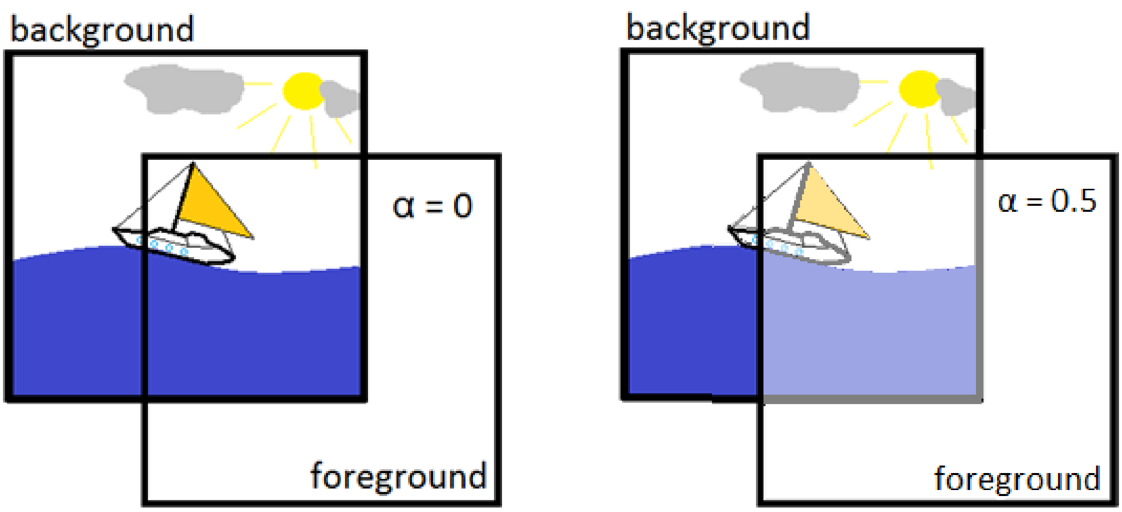


Figure 35: Sailing boat image alpha blended with a white foreground image with the alpha values of 0 and 0.5. With the 0.5 value, the hues are faded and the colors appears to be less saturated.

If the background image is considered to be the color image in Figure 30 and the foreground image to be the grayscale image in Figure 28, then the new image will contain information from both images. The details and contrast will come from the foreground image while the temperature data comes from the background image. (Jayaraman, 2011)

3.2.1.2 Concept 1: manipulation in YCbCr color space

Inspired by the fact that FLIR thermal cameras use the YCbCr color space to represent colors, another approach to mix grayscale information and color information was created rather than traditional alpha blending. The second way to mix the two images together is to manipulate the two images in the YCbCr color space and create a new image. The Y (luminance) value in the new image is taken directly from the grayscale image and the Cb and Cr values comes from the colored image. Figure 36 describes how the luminance is taken from the grayscale image and the Cb and Cr values comes from the color image. In the grayscale image, every pixel's R, G and B value are identical (because it is only different tones of gray), for example, one pixel could have the RGB value of (0.7, 0.7, 0.7) and another (0.2, 0.2, 0.2). Figure 36 displays the approach, what is noted is that the Cb and Cr values from the grayscale image are discarded. This is because in a grayscale image represented by the YCbCr color model, the Cb and Cr values are ≈ 0.5 for all the pixels and thus all the information and contrast in the grayscale image is in the luminance channel. The Y values from the color image is also discarded.

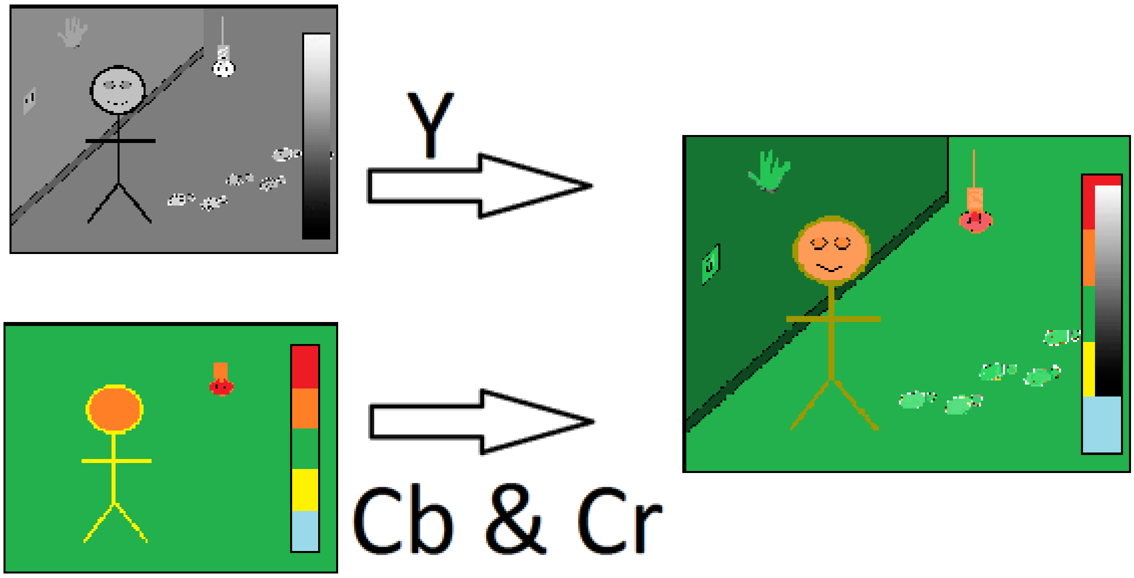


Figure 36: Luminance from grayscale image and blue chrominance and red chrominance from color image.

3.2.1.3 Concept 1: manipulation in HSV color space

The fact that the luminance information in the YCbCr color space affect the colorization to a certain degree, another approach is also explored. This third approach to concept 1 is to manipulate the hue, saturation and brightness values. This is very similar to the previous approach with the YCbCr color model, except that in the HSV color space, the brightness is more separated from the colors than the luminance is in the YCbCr color space. One could guess that this approach conserves the colors better than the previous two with the support of the equation given in the chapter Conversion between color spaces 2.5.2.

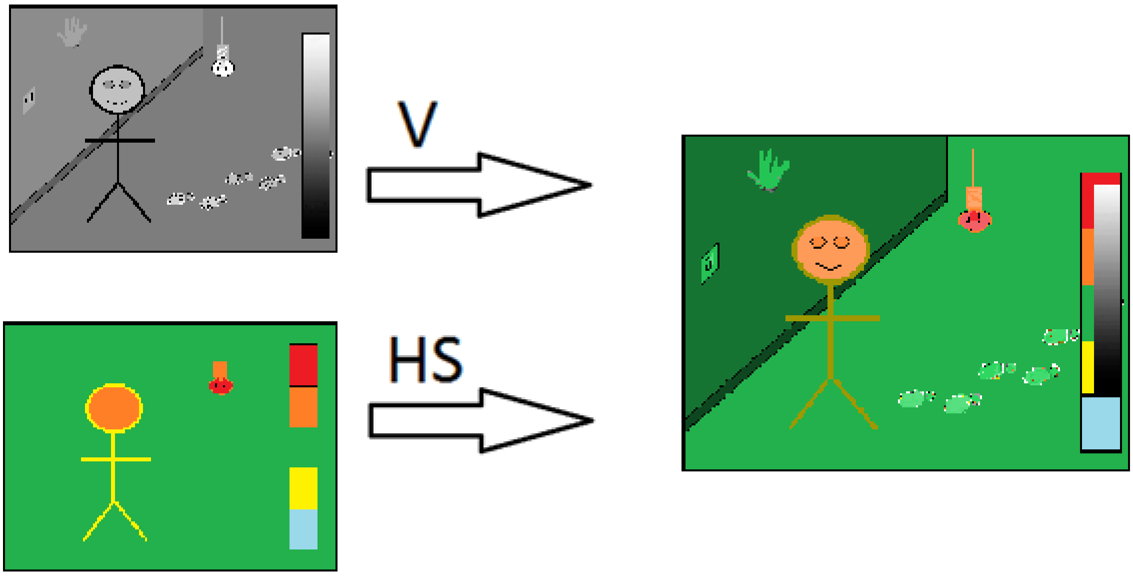


Figure 37: Brightness (V) from grayscale image and hue and saturation from color image.

The HSV approach is very similar to the YCbCr approach as one can see in Figure 37. The difference is how this brightness value is calculated. Where the brightness value in this approach only depends on the largest RGB value (recall that the Brightness = Max(RGB)) while the YCbCr approach calculated the luminance by weighting the difference RGB values and taking into account the color green more than red and blue. This is why both these approaches are worth looking into.

3.2.1.4 Refining concept 1

The three approaches explained earlier all try to achieve the same thing, combining a grayscale image with a color image while maintain the color to temperature matching in the color image and the high contrast from the grayscale image. When these three approaches are implemented and tried by aiming the camera towards the test setup, the images seen in the figures below is produced.

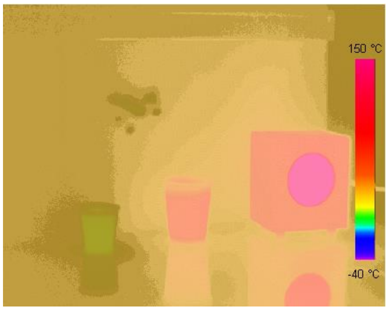


Figure 38: Alpha blending

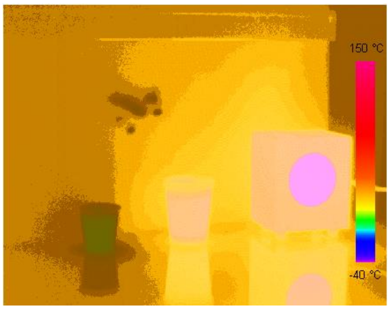


Figure 39: YCbCr

Figure 40: HSV

Figure 38 shows a blended image with low saturated colors, Figure 39 shows saturated colors but the color white is more prominent than it should be. Figure 40 shows saturated colors with no white colors. The three criteria for the master thesis and how the three different approaches fulfill these goals are presented in Table 8.

	Alpha blending	*YCbCr*	*HSV*
Color to temperature matching	The colors are affected quite much by the underlying grayscale which gives the effect of colors appearing different even though the temperature is the same. Not good.	The varying value of the luminance (Y) affects the colors more than expected and some colors appears too bright when combined with the luminance. The color white appears too much, which is bad because the temperature of the color white does not appear in the palette.	The colors feels like they are absolutely connected to temperature because it is only the brightness that is varied. The goal is almost fulfilled but it can be hard to connect the less bright colors in the image to the more bright colors in the palette.
Contrast	Bad contrast because the whole image seems blended and non-saturated.	Very good because the color white is associated with hot areas and the cold areas are very dark colored.	Good because cold areas appear very dark while hot areas appears to have high brightness combined with strong colors.
Intuitive	The palette and the vague connection between color and temperature makes it a little intuitive but it is hard to really feel which objects that are hotter than other because of the low saturation.	Hot objects really feels hot because they are almost completely white.	It is intuitive which objects that are hotter than others because of the colorfulness. Hotter objects appears to have more color than colder objects.

Table 8: A qualitative comparison between the three different approaches to concept 1.

Based on Table 8, the approach with HSV color space manipulation is chosen to move forward with and the two other alternatives are discarded. This decision was made based mainly on Table 8 but also on evaluation with co-workers at FLIR who provided their professional opinion regarding manipulation in different color spaces and the effects on color content.

3.2.2 Concept 2: repetitive sinus wave pattern

Concept 2 is based on combining grayscale for contrast with color for temperature interpretation like concept 1. Concept 2 is needed because the contrast in concept 1 was labeled as too low. In concept 2, both color and grayscale are locked to temperature, unlike concept 1 were only the color is locked to temperature.

The idea is to implement the more advanced features so that new users can benefit from these features without having to tune in the camera by themselves. The basic idea is this:

- The temperature span is locked to a specific range. In this master thesis it is the camera temperature range which is -40 ° C to 150 ° C. All temperatures above or below these temperatures will be saturated.
- The palette is locked to this range by creating a palette with intuitive coloring in this temperature range.
- The contrast is increased by letting the brightness vary in the palette. This is achieved by variations of brightness when working in the HSV color space. The variation is periodical with a sinus curve with the following expression: $0.6 + 0.4 * \sin(x)$ where x is one dimensional coordinates along the palette, see Figure 41. The brightness is varied between 0.2 and 1 (0.6-0.4 to 0.6+0.4).

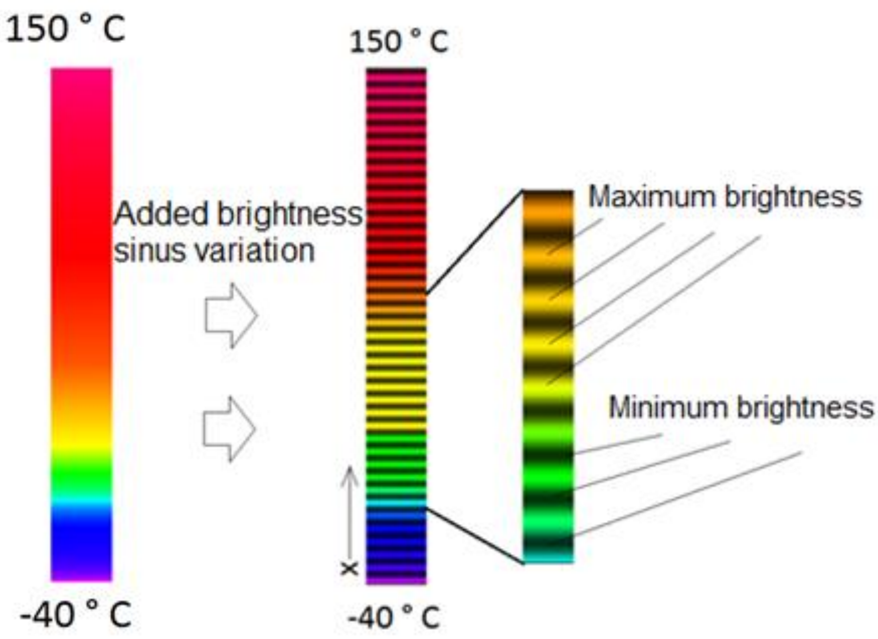


Figure 41: The concept 2 palette is created by adding a sinus variation in brightness across the whole palette resulting in higher contrast.

The temperature values in the image are mapped to colors in the palette, and since the colors in the palette are associated with constant temperatures, the same temperature will always have that specific color.

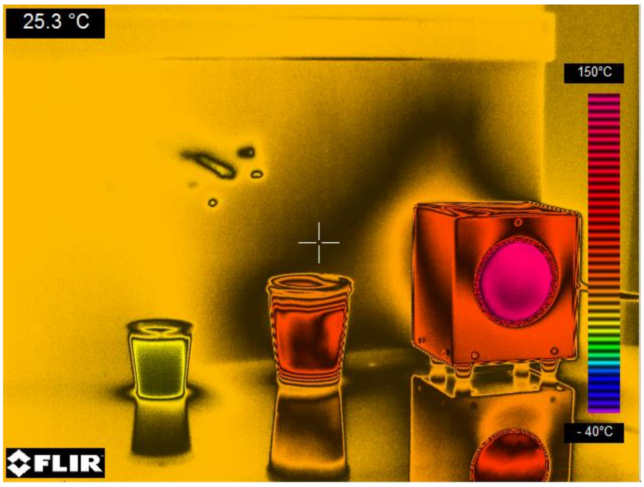


Figure 42: Concept 2.

An artefact originating from the palette used in concept 2 is the stripes that is created in areas with a large temperature gradient.

3.2.3 Concept 3: one sinus wave per color

The stripes artefact associated with concept 2 (visible in Figure 42) resulted in the need for another concept similar to concept 2 but without the artefacts, but maintaining the high contrast. Concept 3 is a variation of concept 2. The difference is that instead of having the brightness vary all over the palette in a sinus pattern. The brightness is varied, but only one period over each color. For example, the color green is assigned one period of brightness variation and the same with the other colors. See Figure 43 for clarification.

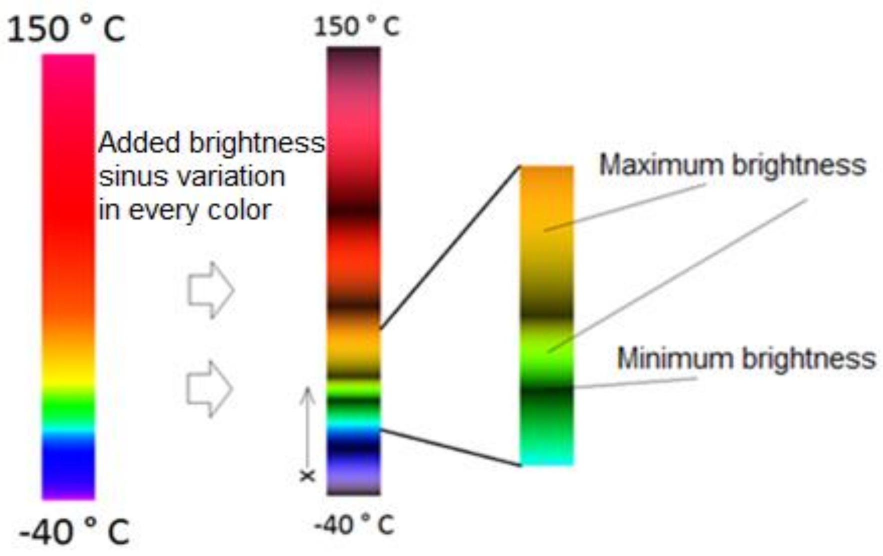


Figure 43: The concept 3 palette is created by adding a variation in brightness in each color.

The contrast in concept 3 is lower than concept 2. This is because the stripes provided contrast even though they were artefacts and decreasing the number of variations resulted in lower contrast.

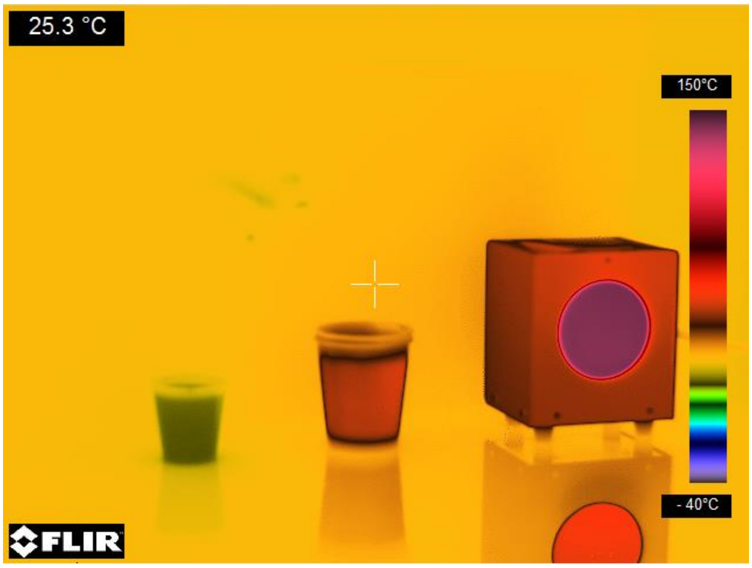


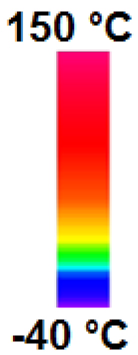
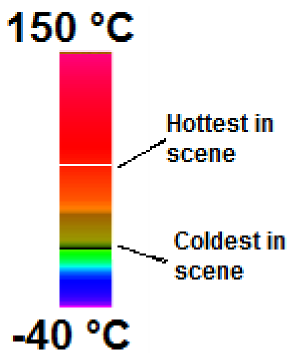
Figure 44: Concept 3.

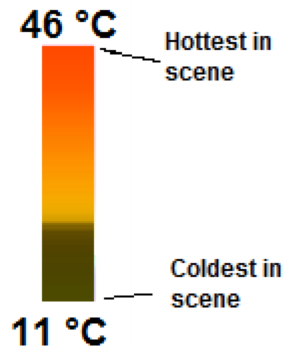
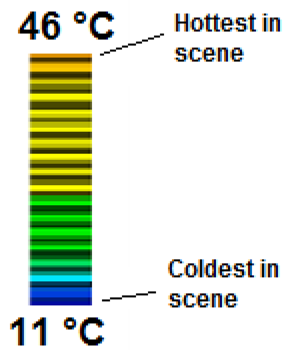
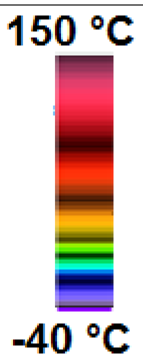
3.2.4 Color scale concepts

All the three concept above colorize an infrared image in different ways but there are much more information that also can be showed to increase the intuitiveness of the colorization, such as the temperature span, crosshair for spot thermometer measurements and the color scales. Figure 45 shows how this information can be displayed when using the iron palette.

Figure 45: Besides the image itself, the iron color scale is shown with its maximum and minimum temperature, a crosshair is in the middle of the image and the temperature of these pixels are shown in the upper left corner of the image. Without the palette and temperature span, the image would be very difficult to interpret.

If one would use this approach and display the image with its palette in the concepts described earlier, there is a risk that the user will be confused because the locked and large span of the palette combined with a grayscale that changes depending on the scene temperature span (in concept 1 only). Several different visualizations of the color scales were developed, to support the new fixed color to temperature palette (Table 9).

Concept 1	
1i) No grayscale information in the palette and the temperature span in the scene does not affect the way the palette is presented. Because the image is colorized not only by the palette colors but also the grayscale from the grayscale image, it can be a little hard to tell which temperature each pixels have. The palette doesn't tell exactly how each temperature is presented in the image because the lack of grayscale information.	
1ii) Grayscale information is shown in palette, this makes the image correspond to the palette color in both brightness and hue. The hottest and coldest temperature in the scene is marked in the palette with lines, giving the user a sense of what temperature information the scene contains.	

1iii) Only the current temperature span is visible in the palette. The palette is updated dynamically for every frame and how much of the palette is to be shown is decided by the dynamic temperature span in the scene. This gives minimally of information to the user as every color in the palette is also to be found in the image but information about temperature that lies outside the current span is not shown.	
Concept 2	
2i) The whole palette is shown independent of the temperature span. All the information in the image is shown in the palette but if the temperature span in the scene is small, it can be difficult to read exact temperatures in the palette. If the current temperature span would be shown in the palette as lines indicating maximum and minimum temperature in the palette, the user might be confused because there is already a large amount of "lines" from the sinus variation in brightness in the palette.	
2ii) Only the span of the scene is shown in the palette, hopefully making it much easier to see which pixels that has which temperatures. Only showing the current temperature span also gives more information to the user regarding the whole scene that he or she is looking at.	
Concept 3	
3i) The whole palette is shown independent of the temperature span. Makes it hard to connect temperatures to colors as the whole palette is shown and it might be difficult to connect colors in the image to colors in the palette.	

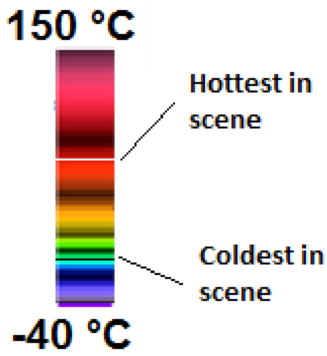
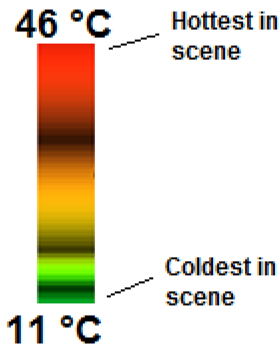
3ii) The whole palette is shown, but the maximum and minimum temperatures are marked by lines in the palette to give the user a feeling where to look for temperature and the overall temperature landscape in the scene.	
3iii) Only the current span is seen in the palette. This only gives the user information that is relevant at the moment. The span changes as the user aims the camera at different scenes.	

Table 9: Different ways to present information to the user.

3.3 Procedure: evaluation

To compare between the concepts an evaluation by selected test subjects were made. These test subjects all work at FLIR Systems and are all experienced thermal camera users. They were introduced to the current problem of today and the test setup with a computer, thermal camera, heat source, moist stains and room temperature objects. They were then free to look around and examine their surroundings with the IR camera. For the evaluation, the approaches 1i, 2i, 3i were chosen. The different versions were labeled according to Table 10.

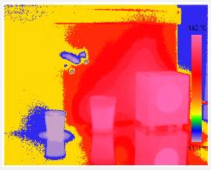
Iron palette	Dynamic base palette	Concept 1: HSV (1i)	Concept 2 (2i)	Concept 3 (3i)
				
Labelled as **1A**. This is the most used palette today and is included to see how the different concepts is rated relative to this iron palette.	Labelled as **1B**. This palette is the same palette as the one used in all the previously mentioned concepts, except that it is not locked at a temperature range and is allowed to vary across the temperature span in the current scene.	Labelled as **1C**. The alpha blending and YCbCr approach were not evaluated by FLIR employees. This is the technique with HSV manipulation.	Labelled as **1D**.	Labelled as **1E**.

Table 10: Labels of different versions of the generic solutions.

The test subjects rated the contrast and color to temperature matching. The contrast was tested by examining moist stains and small temperature differences. The color to temperature matching was tested by using the crosshair which tells the temperature and comparing the color of items while checking their temperature. The test subjects were told to rate the categories in a scale from -5 to 5.

3.4 Results

During the initial test, it was decided to be enough with FLIR employees as test subjects, even though they may not be the best suited persons for the task because the prototypes are more aimed towards non-experienced users with no experience of operating an IR camera.

	Contrast					***Color to temperature***				
Test subject	**1A**	**1B**	**1C**	**1D**	**1E**	**1A**	**1B**	**1C**	**1D**	**1E**
1	4,5	4,5	3,0	-3,0	-4,0	-4,5	-4,6	4,0	1,0	2,5
2	3,0	4,0	2,0	1,0	-3,0	-2,0	-3,0	3,0	3,0	4,0
3	4,3	3,2	2,1	2,0	-2,3	-4,0	-4,0	2,3	0,6	4,0
4	4,4	4,5	3,0	-1,0	-3,4	-4,6	-4,6	1,0	0,3	3,0
Total	16,2	16,2	10,1	-1,0	-12,7	-15,1	-16,2	10,3	4,9	13,5
Standard deviation	0.6	0.5	0.5	1.9	0.6	1.0	0.7	1.1	1.1	0.6
Mean	4,1	4,1	2,5	-0,3	-3,2	-3,8	-4,1	2,6	1,2	3,4

Table 11

The total value is calculated by adding all values together, the mean is then calculated by dividing this with four (Table 11). Once the mean is calculated, the solution mean can be calculated, which is the contrast mean and color to temperature mean divided by two (Table 12).

	1A	1B	1C	1D	1E
Solution mean	0,1	0,0	2,6	0,5	0,1

Table 12

The value in calculating the solution mean is to see how well the solution performs as an average based on all the criteria and can be used as a way of ranking the solutions. The contrast and color to temperature values can also be used as horizontal and vertical axes in a coordination grid. If the mean values for each solution is used, each solution is represented by a point in this plane, as seen in Figure 46.

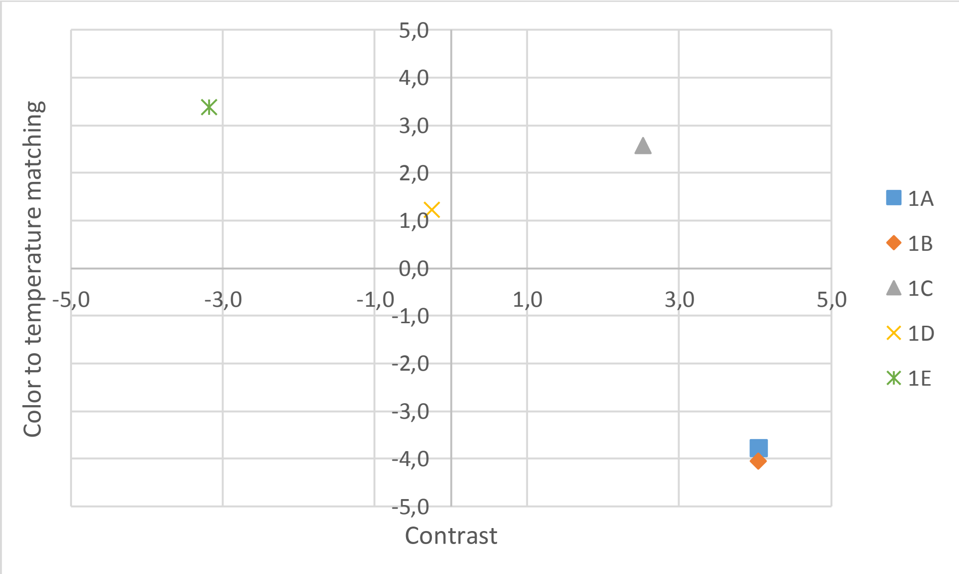


Figure 46: The contrast and color to temperature plane, mean value for each solution is represented by a point in this space.

During the evaluation, the test subjects made some comments regarding the solutions:

-"1C feels honest."

-"It is confusing in 1D when black can be hot and cold, how to know when it is what?"

-"1E feels harmonic."

-"In 1E, black feels cold, not always true in image though."

It was also mentioned that a generic solution might be interesting but custom fitted solutions was of great interest in the future.

3.5 Discussion

The goal of creating a generic colorization of thermal images was to achieve consistent color to temperature matching which would eliminate the confusion that the automatic coloring caused, maintain good contrast and provide an intuitive presentation to the user. The result showed that the test subjects were able to understand the connection between color and temperature even though the brightness varied to a high degree. This is mainly due to the brightness consistency which makes a specific color look like that specific color even though it is exposed to different lighting. It is clear from the results that the test subjects experienced the contrast better in the two solutions were the palette stretches itself across the current temperature span (1A, 1B) while the contrast with an absolute color palette was experienced as worse. The rating of the different concepts was similar between the test subjects and each solution was concentrated in some clusters which indicated that all the test subjects experienced the solutions quite similar.

The contrast in 1E was regarded as worst by all the test subjects and was ranked with negative rating by everyone. The color to temperature matching was however rated as high with 1E which means that they understood that the color was consistently matched to temperature but as a result of this, the contrast was worsened. The spread was the largest with 1D which implies that the intuitiveness is low because they understood it quite differently. Everyone rated the 1D color to temperature matching positive. 1C was rated the *"best"* with high values in contrast and color to temperature matching and the highest solution mean value. The contrast ranking of 1C was very similar between the test subjects while the spread of the color to temperature matching was a little larger. The results indicated that the test subjects who all works with thermal cameras on a daily basis understood the color to temperature consistency in 1C. They felt that a specific color always was related to a specific temperature. It is interesting how different they rated the contrast in 1D, it received -3 from one person which is very low. It might be because the experienced test subjects are so used to having maximum contrast from the automatic color scale that they demand more than what 1D can deliver.

The evaluation also showed that there was a need for application specific solutions were the solution is custom fitted to meet certain criterion. A custom fitted solution able to achieve color to temperature constancy would be of interest because it would mean that the solution could be made more intuitive in a specific field rather than intuitive as a generic solution with no specific user scenarios. The next phase in this thesis explores the ability to create such solutions.

4 Phase 2: application specific solutions

In this section, the application specific solutions method, result and conclusion are presented. Once the generic concepts have been realized, further steps is made to customize them to fit certain needs where the colorization needs to be more adapted to a specific purpose. A person inspecting food in freezers may be confused if the camera would display the full temperature range, and this would not be intuitive or meaningful colorization for the task of food inspection. Instead the colorization needs to be designed in a way that makes the user able to understand what the camera displays. When the camera is marketed as an application specific tool, intuitive colorization means something other than when the camera is marketed as a generic thermal camera. Specifically building inspection and food inspection were selected as test applications. A general idea behind the application specific solutions is to limit the presentation of data to data that is useful for the current application, which hopefully results in a more intuitive presentation of data.

A building inspector may look at moist stains, air leakage, using the camera just for orientation in dark areas or localizing hot water pipes. Many of the properties that inspired the generic solutions developed in phase 1 with large temperature range and high contrast on small temperature differences are highly relevant for building inspections particular. Therefor the generic solutions from phase 1 will be evaluated as building inspection solutions in phase 2. This means that 1A, 1B, 1C, 1D, 1E will be treated as building inspection concepts rather than generic concepts in phase 2.

Another application specific field is food inspection, the temperature of food has to be measured multiple times during the journey that most food make from its first step of production to the final stage when it is served. When food is stored in a freezer or refrigerator, the temperature has to be in a specific interval and when food is cooked, a certain temperature has to be reached to guarantee that the food is free from microbes and pathogens. Errors in the handling of food can cause great damage to companies and customers can get seriously ill if sufficient temperatures are not achieved. (Colm P. O'donnell)

In United States alone, there are 3000 deaths annually caused by contaminated food, many deaths could have been avoided with correct temperatures throughout the whole food process. (Cdc, 2011)

Inspection situations can be a truck driver transporting frozen food a long distance and to ensure that the cold chain is kept under some threshold temperature. This would take a tremendous amount of time with an ordinary thermometer or an IR spot thermometer, but with a thermal camera, the truck driver is able to scan the whole inside of the truck very fast and if there are anomalies, he can take a closer look at that region of interest.

The exact temperatures are for this master thesis not the main focus as it is always possible to adapt the solutions to warn for different temperatures in the future when designing a real product. The temperatures presented herein are just for evaluating the solutions. In this master thesis, four different food inspection solutions will be presented and evaluated. All of them are intended for inspection of fridges.

4.1 Method

4.1.1 Equipment

The equipment used in phase 2 is identical to phase 1 as it is the same camera used in both phases. The reference images is the same for the building inspection solution as for the generic solution but the reference image is different for the fridge inspection solution, which can be seen below.

The reference image used for comparison is the view of a fridge. This view is showed in the popular iron palette in Figure 47.

Figure 47: Reference image viewed with the iron palette, the scene is a fridge.

4.2 Procedure: concept development

4.2.1 Building inspection

The building inspection solutions consist of 1A, 1B, 1C, 1D and 1E which was explained in phase 1. For the evaluation of these concepts as building inspection solution, two more concepts are added, 1F and 1G. These are explained in the evaluation chapter.

4.2.2 Fridge inspection 1: visual thermometer

The first food inspection prototype is simply 1C but with the palette imitating a thermometer (Figure 48) to create the feeling of a visual thermometer where the user can estimate the temperature by looking at the thermometer (palette) and determine if a fridge fulfills the different criteria. The idea behind this is to emphasize that the temperature should be connected to a specific color and the user should learn which color to look for when searching for a specific temperature.

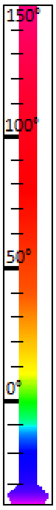


Figure 48: Palette imitating the look of a thermometer, unit in thermometer is °C.

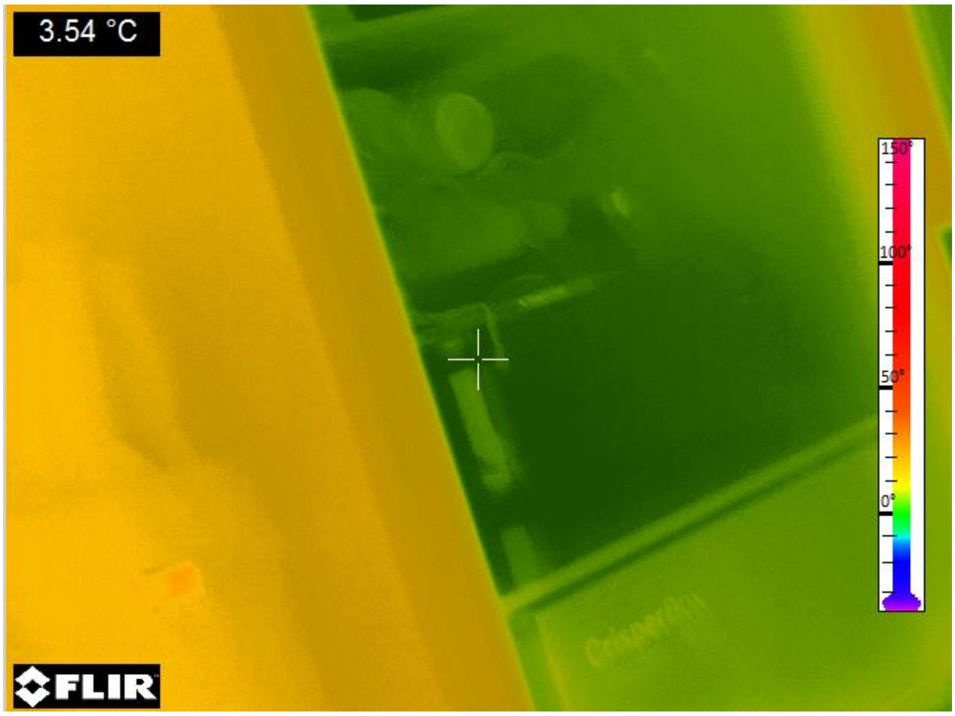


Figure 49: Visual thermometer with a picture of a thermometer (marks for different temperatures) instead of the ordinary color scale, the units in the thermometer is °C.

4.2.3 Fridge inspection 2: blue below

The second fridge inspection prototype is constructed as a variant of 1C. The difference is that the base palette is changed from a palette designed to intuitively cover the whole temperature range of the camera to a palette with essentially only two colors, blue and red. Where blue symbolize temperatures that are accepted and red symbolizes temperatures that are too high or at least above a predefined threshold value. The saturation of the palette is set to linearly change between 1 and 0.5 as seen in Figure 50. This is to make the transition between blue and red less extreme and abrupt.

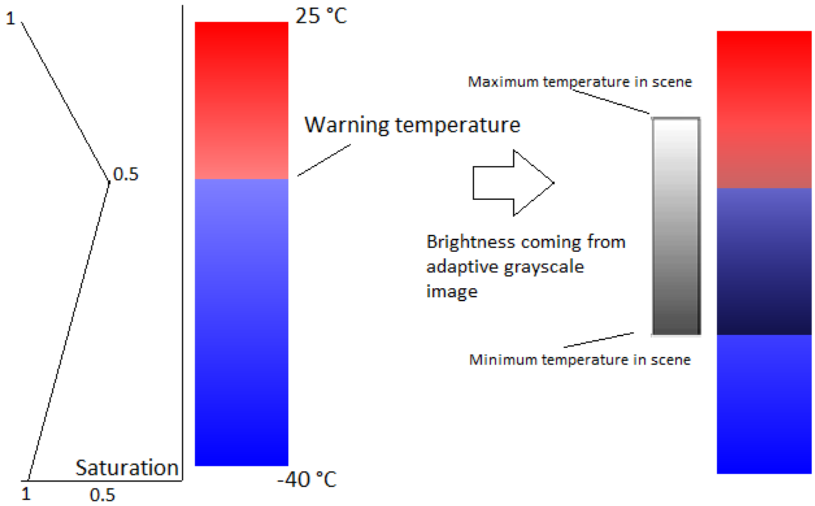


Figure 50: Fridge inspection palette with varying saturation and grayscale information coming from grayscale adaptive image, functioning as 1C.

As the grayscale information (the brightness of the colors) comes from an adaptive grayscale image, there will be good contrast in the image even if the image saturates itself in the palette and all the pixels turn red because the grayscale information will not be saturated. The color palette is locked to the small temperature span of -40 °C to 25 °C. For the evaluation of this prototype, the warning temperature can be set to 2 °C, 4 °C, 6 °C, 8 °C or 10 °C.

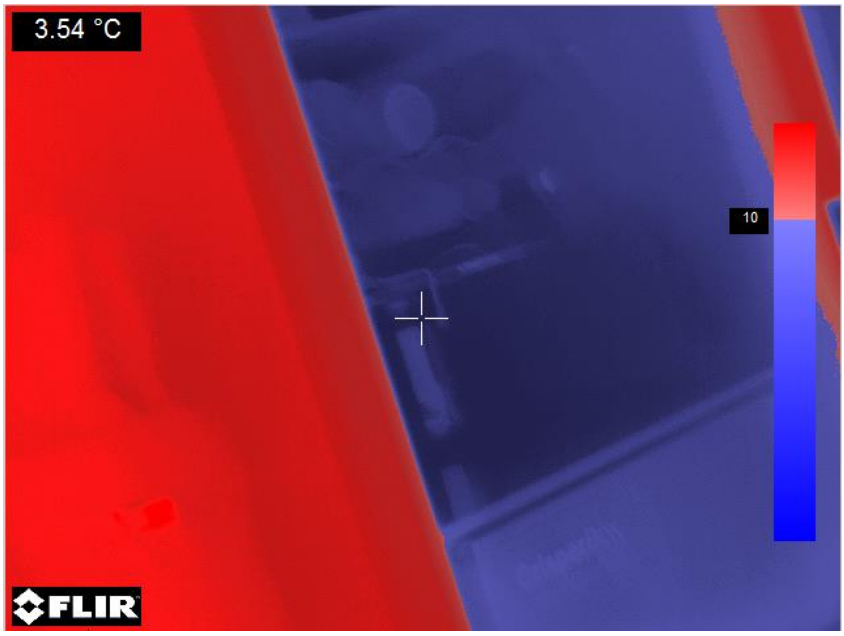


Figure 51: Warning temperature is set to 10 °C, everything in the fridge is blue which indicates that the temperature is lower than 10 °C.

Figure 51 shows the blue below solution. The grayscale data is histogram equalized to increase the contrast in the image. This is possible without affecting the color to temperature matching because the grayscale is not connected to temperature.

4.2.4 Fridge inspection 3: gray normal

The third fridge inspection prototype is probably the most computational power demanding because it works like 1C but it also has another grayscale image in its procedure. It has, as 1C one grayscale image that adapt itself to the current temperature span, and it has a color palette giving colors to the image. But it also has a grayscale image that is only active in the predefined temperature span of 0 °C to 10 °C. This temperature span is chosen because in this interval, the food in the fridge will have an accepted temperature, (can as mentioned before, be changed to match real world correct values if implemented as a real feature in IR cameras). It is designed to give the user a feeling that areas that are in grayscale are accepted and areas with temperatures above 10 °C will be red. Areas below 0 °C will be colored in blue to indicate the danger of too cold objects. The demanding calculations in this prototype comes from the fact that the grayscale area in 0 °C to 10 °C are treated as a separate image, it is constructed like this so the image can be histogram equalized, which will increase the contrast in the image and give a better image to the user. The whole span grayscale image is then combined with the color palette in the areas where the temperature is below 0 °C and above 10 °C. In the interval between, the camera will only show the histogram equalized grayscale image. The constructed image can be seen in Figure 52.

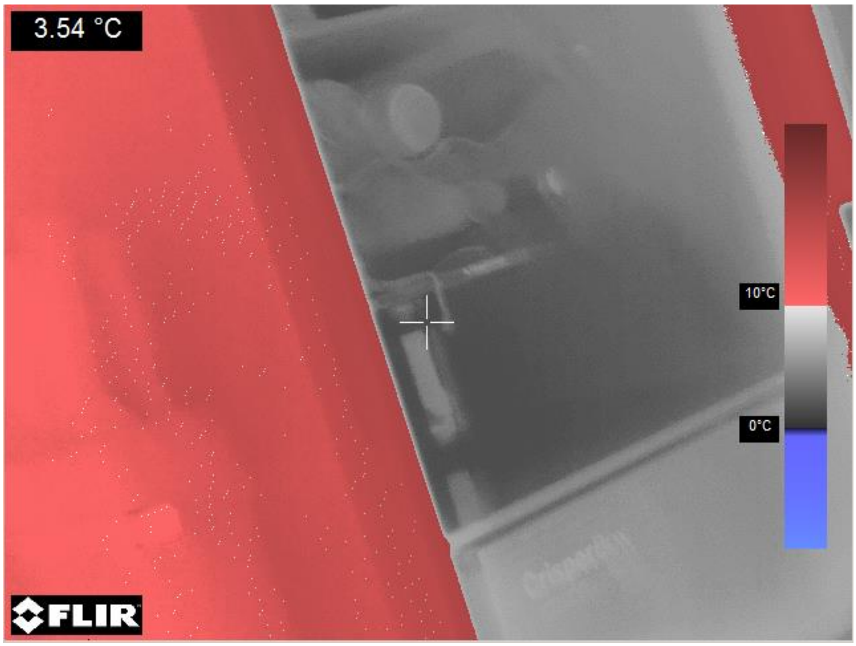


Figure 52: Gray normal, accepted temperature is colorized in grayscale color.

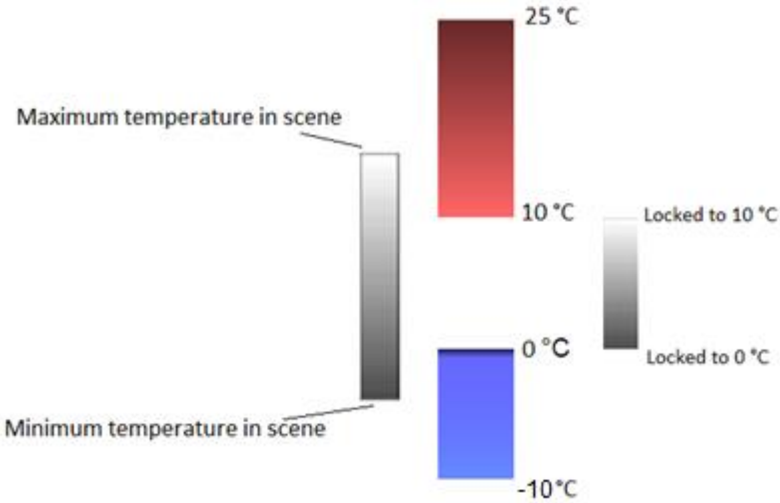


Figure 53: The general idea of the solution. Notice that the computational demands comes from the fact that there are three images for each final image. Image1 (left): Grayscale image covering the whole temperature span. Image2 (middle): color palette which colorizes blue below 0 °C and red above 10 °C. Image3 (right): another grayscale image, which is locked between 0 °C and 10 °C.

When the user is looking at a scene where the temperature is between -3 °C and 20 °C, the objects at -3 °C to 0 °C will be dark blue to a little brighter blue (still quite dark though, the grayscale is smeared out across the whole span). Objects between 0 °C and 10 °C will be in grayscale (from almost black to almost white). Objects between 10 °C and 20 °C will be colorized as red, with increasing brightness.

4.2.5 Fridge inspection 4: red hot

The fourth fridge inspection solution is quite simple, it has a palette that colorizes temperatures above 10 °C in red and temperatures below will be in grayscale. The grayscale is inspired by solution 1C, meaning that the grayscale adapt itself to the current temperature span and is not locked to temperature in any way. Objects with temperatures below 10 °C has no predefined color values, they are colorized in the adaptive grayscale color and are thus not connected to temperature.

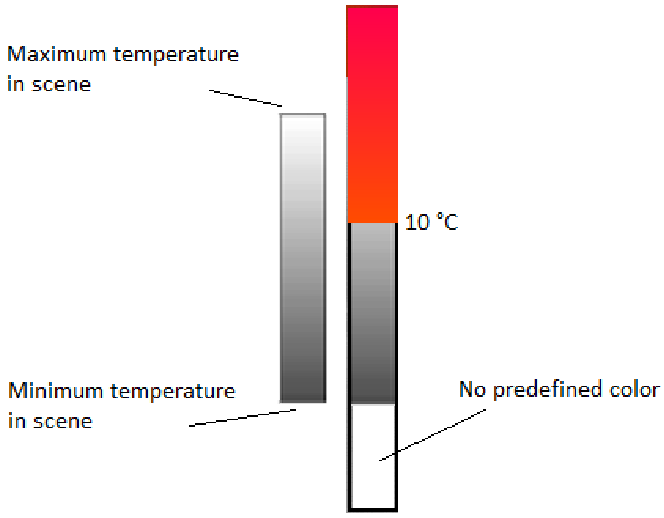


Figure 54: Red hot food inspection solution.

Figure 55: Temperatures below 10 °C will be colorized in the adaptive grayscale color. Notice that the grayscale is not shown in the color scale.

The color scale presented to the user is only colorized at values above 10 °C (Figure 55). It may not be that extremely intuitive, because the user does not know how temperatures below 10 °C will be colorized based on the color scale.

4.3 Procedure: evaluation

The evaluation is divided in two parts, the building inspection evaluation and the food inspection evaluation. Both are evaluated by non-experienced test subjects.

4.3.1 Building inspection

The evaluation of building inspection solutions includes the solutions 1A, 1B, 1C, 1D, 1E, 1F and 1G. 1A-1E was explained in Table 10. 1F is very similar to 1C and the only difference is how the color scale is presented. In 1C, the whole camera temperate range is presented (-40 ° to 150 °C) and in 1F, it is only the current temperature span of the image that is presented and the grayscale is visible in the color scale, which it is not in 1C. The color scale presentation is thus limited by the current temperature span. The image itself will be identical, but the color scale will be zoomed in with 1F. 1G is identical to 1F, except that the grayscale is allowed to vary from 0 to 1 instead of 0.3 to 1 as in 1F and 1C. The grayscale is also showed in the color scale in 1F.

*Figure 56: Labelled as **1F**, essentially the same as 1C but with zoomed in color scale.*

*Figure 57: Labelled as **1G**, same as 1F except that the grayscale brightness goes from 0 to 1, instead of 0.3 to 1.*

The building inspection evaluation was performed by test subjects not familiar with thermal cameras. None of the test subjects had held a thermal camera before the evaluation. Eight persons conducted the evaluation. The environment of the evaluation was a room with objects representing a possible user scenario. There were moist stains, hot and cold objects and ordinary room temperature objects.

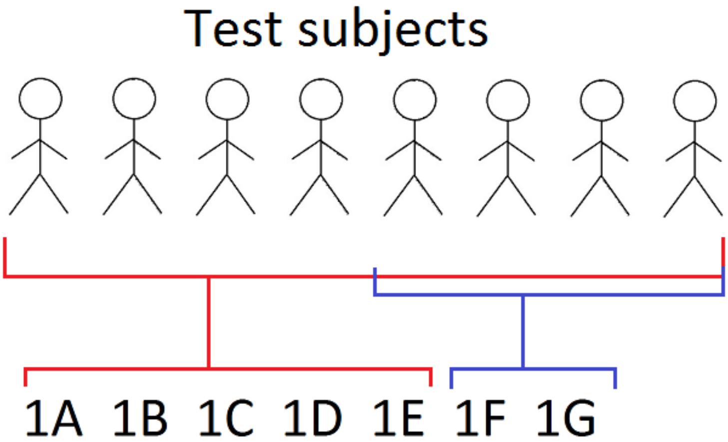


Figure 58: Eight test subjects and the solutions that they evaluated, none of them were familiar with thermal cameras.

The evaluation procedure lasted on an average of one hour per test subject. The test subjects were given an evaluation form, found in appendix B. There were three categories for each solution and they ranked every solution regarding these three categories that were contrast, color to temperature matching and intuitiveness. Every one of the eight test subjects evaluated 1A - 1E, while only half of these test subjects also evaluated 1F and 1G (Figure 58). The starting order of the evaluation was randomized, which means that not all started with for example 1A.

4.3.2 Food inspection

For the food inspection evaluation, the iron palette was included because this is the most used palette today. All the evaluated solutions are seen in Table 13.

Iron palette	Visual thermometer	Blue below	Gray normal	Red hot
				
Labelled as **2A**. This is the most used palette today and is included to see how the different concepts is rated relative to the iron palette.	Labelled as **2B**. Identical image as 1C except that the color scale is changed to a thermometer.	Labelled as **2C**. Blue below a certain temperature and objects warmer will be red. Contrast comes from adaptive grayscale.	Labelled as **2D**. Grayscale colorization in "normal" areas where the temperature is accepted.	Labelled as **2E**. Everything warmer than a certain temperature will be colorized as red. Contrast comes from adaptive grayscale.

Table 13: Different food inspection solutions.

The test subjects were free to inspect a fridge and a freezer. It was a regular fridge containing food. In the fridge there were objects with temperatures that were either too high, too low or just ordinary fridge temperature objects. There were three categories that the test subjects had to take into account: how well they recognized objects (*"That package of milk sure looks like a package of milk!"* and so on), how well they found deviations (*"That object is too hot for the fridge!"*) and how intuitive the whole solution was. The test subjects filled out a form were they ranked the solutions in these three categories. This form can be found in appendix B.

4.4 Results

The results are presented separately for the building inspection and the food inspection evaluations. Both of the results are from non-experienced users with no prior knowledge of thermal cameras.

4.4.1 Building inspection

The test subjects ranked the contrast, color to temperature matching and the intuitiveness according to tables below.

	Contrast						
Test subject	**1A**	**1B**	**1C**	**1D**	**1E**	**1F**	**1G**
1	3,0	0,0	3,0	4,0	-1,0		
2	2,0	3,0	1,0	4,0	-1,0		
3	3,0	-3,0	-4,0	5,0	-5,0		
4	2,0	3,0	0,0	3,0	1,0		
5	3,5	-1,5	4,5	4,0	0,0	-0,5	2,5
6	4,5	1,0	4,5	1,0	-2,0	-2,0	3,0
7	3,0	2,0	4,0	4,0	1,0	1,0	3,0
8	3,0	-3,0	4,0	5,0	3,0	2,0	0,0
Total	24,0	1,5	17,0	30,0	-4,0	0,5	8,5
Standard deviation	0,8	2,3	2,8	1,2	2,2	1,5	1,2
Mean	3,0	0,2	2,1	3,8	-0,5	0,1	2,1

Table 14

Test subject	1A	1B	1C	1D	1E	1F	1G
	Color to temperature matching						
1	-3,0	2,0	-2,0	0,0	-4,0		
2	4,0	2,0	-2,0	1,0	3,0		
3	0,0	0,0	-5,0	-5,0	-5,0		
4	0,0	3,0	3,0	2,0	3,0		
5	-3,5	-2,5	3,0	3,5	2,5	-2,0	-2,5
6	-4,0	-4,0	0,5	-4,0	-2,0	-2,0	0,0
7	0,0	1,0	-1,0	1,0	1,0	1,0	0,0
8	-3,0	-3,0	3,0	5,0	0,0	4,0	-2,0
Total	-9,5	-1,5	-0,5	3,5	-1,5	1,0	-4,5
Standard deviation	2,5	2,5	2,8	3,2	3,0	2,5	1,1
Mean	-1,2	-0,2	-0,1	0,4	-0,2	0,3	-1,1

Table 15

Test subject	1A	1B	1C	1D	1E	1F	1G
	Intuitiveness						
1	2,0	-1,0	-2,0	-3,0	-4,0		
2	2,0	1,0	1,0	1,0	3,0		
3	5,0	3,0	-5,0	4,0	-5,0		
4	3,0	2,0	3,0	1,0	3,0		
5	1,5	0,5	4,5	2,5	2,0	2,0	2,5
6	4.5	-4,5	4,5	-4,5	-2,0	-2,0	2,0
7	1,0	1,0	1,0	1,0	1,0	1,0	2,0
8	2,0	2,0	4,0	4,0	4,0	3,0	3,0
Total	16,5	4,0	11,0	6,0	2,0	4,0	9,5
Standard deviation	1,2	2,2	3,2	2,9	3,2	1,9	0,4
Mean	2,1	0,5	1,4	0,8	0,3	1,0	2,4

Table 16

Similar to phase 1, the solution mean can be calculated by adding the three categories together for each solution and then dividing by three (Table 17).

	1A	*1B*	*1C*	*1D*	*1E*	*1F*	*1G*
Solution mean	1,3	0,2	1,1	1,6	-0,1	0,5	1,1

Table 17

In phase 1, there were only two categories and this made it possible to construct a coordination system and position each solution and their mean values. Here in phase 2, there are three categories and it would therefore be needed a three dimensional coordination system which would look messy on a computer. The coordination system with contrast and color to temperature matching can however be created (Figure 59), which is comparable to the one in phase 1.

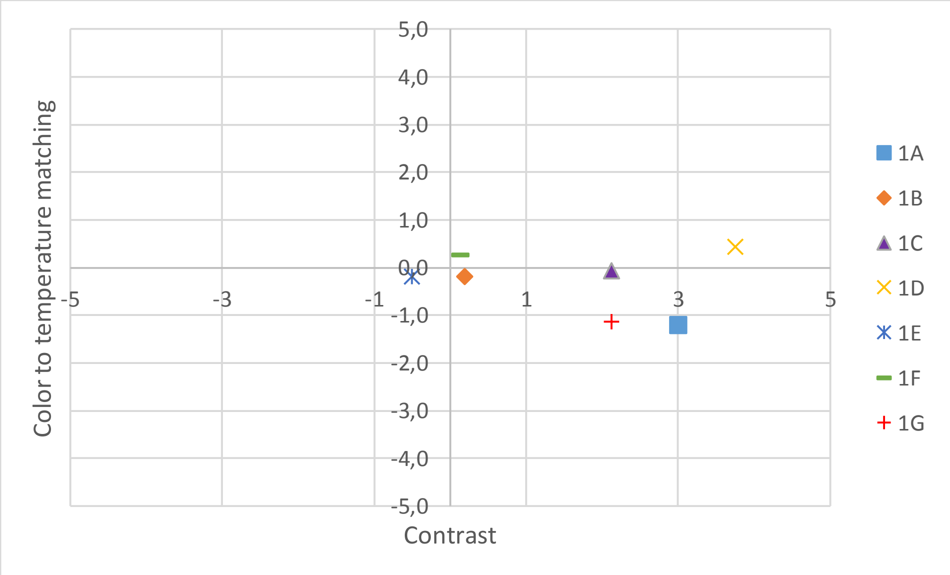


Figure 59: Non-experienced test subjects and their ranking of building inspection solutions (mean values).

4.4.2 Food inspection

The food inspection evaluation was carried out by four test subjects and the results are presented in the tables below.

Recognizing objects

Test subject	**2A**	**2B**	**2C**	**2D**	**2E**
1	2,0	2,0	0,0	-3,0	0,0
2	2,0	4,0	1,0	0,0	0,0
3	4,0	3,0	3,0	0,0	3,0
4	-1,0	1,5	3,0	0,0	3,5
Total	7,0	10,5	7,0	-3,0	6,5
Standard deviation	1,8	1,0	1,3	1,3	1,6
Mean	1,8	2,6	1,8	-0,8	1,6

Table 18

Finding deviations

Test subject	**2A**	**2B**	**2C**	**2D**	**2E**
1	-4,0	-4,0	0,0	4,0	4,0
2	2,0	0,0	4,0	5,0	4,0
3	4,0	1,0	5,0	3,0	4,0
4	3,0	3,0	3,5	0,0	4,0
Total	5,0	0,0	12,5	12,0	16,0
Standard deviation	3,1	2,5	1,9	1,9	0,0
Mean	1,3	0,0	3,1	3,0	4,0

Table 19

Test subject	2A	2B	2C	2D	2E
			Intuitiveness		
1	-4,0	-4,0	-2,0	4,0	3,0
2	2,0	4,0	2,0	3,0	1,0
3	3,0	-3,0	4,0	-4,0	-5,0
4	1,0	2,0	0,0	-1,0	3,0
Total	2,0	-1,0	4,0	2,0	2,0
Standard deviation	2,7	3,3	2,2	3,2	3,3
Mean	0,5	-0,3	1,0	0,5	0,5

Table 20

The solution mean is seen in Table 21.

	2A	*2B*	*2C*	*2D*	*2E*
Solution mean	1,2	0,8	2,0	0,9	2,0

Table 21

Figure 60 shows a similar graph as above, but with food inspection data. The first two categories (recognizing objects and finding deviations) are chosen in this graph.

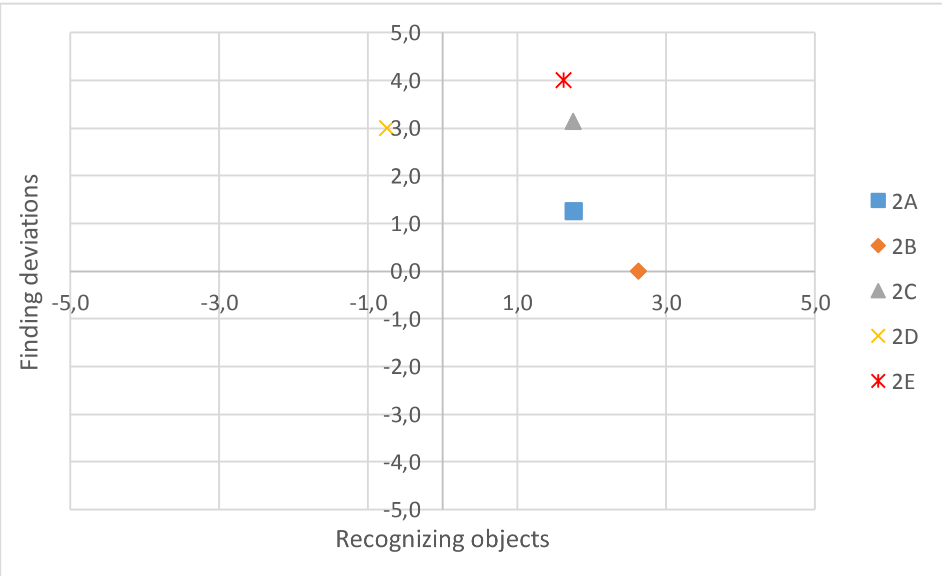


Figure 60: Non-experienced test subjects and their ranking of food inspection solutions.

4.5 Discussion

4.5.1 Building inspection

The goal was to create an intuitive colorization with a constant temperature to color matching that were custom made to fit the needs of a building inspector. The solution with the best total solution mean was 1D with 1.6 on a scale between -5 to 5. This solution also received the highest contrast score and color to temperature matching (even though the standard deviation was quite large). 1D achieved a not so bad intuitiveness score, even though its stripe artefacts could have been difficult to understand. 1G was ranked as the most intuitive with a low standard deviation (a small population also though). It was only 1D and 1F that received a positive mean score on the color to temperature matching. The spread was very large of 1D color to temperature matching, one test subject gave it -5 and another 5. Observing the plane in Figure 60, it is clear that most of the solutions have color to temperature matching around zero and the big difference between different solutions are the intuitiveness score.

4.5.2 Food inspection

The goal with the food inspection solutions was to create an intuitive tool that provided an easy way to detect food that could be potentially dangerous to eat. The test subjects did not have any experience of food inspection and this could have affected the result. A more representative test subject would have been a food inspector with no prior experience of thermal cameras. The evaluation was carried out by four non-experienced users and the highest solution mean score was 2C and 2E. Both 2C and 2E received 2.0 on a scale between -5 and 5. 2E was ranked as very good at detecting deviations while 2C was better at recognizing objects and being intuitive. Every solution received a positive mean score on finding deviations which is to be considered as a good result. 2B had a lower mean value at finding deviation than 2A which probably makes 2B a poor choice for food inspection.

5 Discussion and conclusion

Comparing the results from phase 1 with the phase 2 building inspection results, it is obvious that the test subjects familiar with thermal cameras ranked the contrast in 2B much better, they also ranked the color to temperature much higher for 1C and 1E. This difference can be because of the different background of the two test subject groups. The test subjects in phase 1 were much more experienced and comfortable with thermal cameras and knew what to look for, this most likely affected the results. When non experienced test subjects ranked the intuitiveness, they often thought that they understood a solution but when listening to their explanation and thoughts it was sometimes evident that they in fact did not understood everything and ranked the intuitiveness based on this misunderstandings. This is something that needs to be regarded when looking at the results. If the test persons thinks that they have understood everything, of course they will rank the intuitiveness high.

The evaluation procedures lasted for approximately one hour per person and it is possible that the relatively long time of the procedure might have affected the result. It could have been a better idea to only use one test person for each concept and use much more test persons so that each test person only evaluated one concept. This would require more time and is probably a master thesis in itself but in future work, this is recommended.

To sum up, it is worth considering if this master thesis succeeded in the task of creating an intuitive colorization of thermal camera images with constant color to temperature matching. The answer is not so clear:

- Yes, it was successful because colors are consistent for different temperatures, but there were some issues with the difference in brightness that caused colors to appear different even though they had the same hue. The hue green is green regardless of its brightness but the test subjects considered it a different color when the brightness changed too much.
- In terms of intuitiveness, it was not obvious that the new concepts managed to outperform the existing type of color palettes (e.g. iron).
- The external validity of the results is relatively low because the population of test subjects was too low to draw any substantial conclusions from, rather than that application specific solutions are needed.

6 Recommendations

Based on the results given in this thesis, it is of interest to create more concepts that are aimed more towards a specific user group rather than creating a generic solution that fits all kind of uses. The generic solution was appreciated but it was clear that the test subjects would appreciate a solution that is optimized towards a specific field rather than trying to be good at everything. The goal of creating a solution that is intuitive, color to temperature consistent while having good contrast might be difficult to realize, as this master thesis showed, but more application specific solutions with these properties are realistic to create in the future. A comprehensive study where the needs are thoroughly examined and understood are needed to create an appropriate application specific solution. Who exactly is the target group, are they even interested in buying thermal cameras if the possibility existed, will their company gain anything or is it just another cost for them, these are questions that needs to be addressed in order to create a competitive solution.

In order to create more application specific solution, it might be of interest to create some kind of software elaboration tool that will make the creation of new concepts easier. This software should be able to setup and configure different concepts based on palettes. With this software, development of new concepts could be performed in close contacts with new representative customers.

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8 Appendix

Appendix A - Base palette code

The following code generates the base palette used in concept 1, 2 and 3 in phase 1 and the visual thermometer in phase 2.

```
%allocating memory
palette = zeros(1900, 1, 3);

%purple -> blue
palette(1:200,1,1) = linspace(200,0,200);
palette(1:200,1,2) = linspace(162,0,200);
palette(1:200,1,3) = linspace(200,255,200);

%blue -> green
palette(200:400,1,1) = linspace(0,0,201);
palette(200:400,1,2) = linspace(0,255,201);
palette(200:400,1,3) = linspace(255,0,201);

%green -> yellow
palette(400:500,1,1) = linspace(0,255,101);
palette(400:500,1,2) = linspace(255,255,101);
palette(400:500,1,3) = linspace(0,0,101);

%yellow -> orange
palette(500:800,1,1) = linspace(255,255,301);
palette(500:800,1,2) = linspace(255,100,301);
palette(500:800,1,3) = linspace(0,20,301);

%orange -> red
palette(800:1200,1,1) = linspace(255,255,401);
palette(800:1200,1,2) = linspace(100,0,401);
palette(800:1200,1,3) = linspace(20,0,401);

%red -> lilac
palette(1200:1900,1,1) = linspace(255,255,701);
palette(1200:1900,1,2) = linspace(0,105,701);
palette(1200:1900,1,3) = linspace(0,180,701);

%normalizing to range 0:1
palette = palette / 255;
%changing color model
%from RGB to HSV
palette = rgb2hsv(palette);
%setting saturation and brightness to 1
palette(:,1,2) = 1;
palette(:,1,3) = 1;
%changing color model
%from HSV to RGB
palette = hsv2rgb(palette);
```

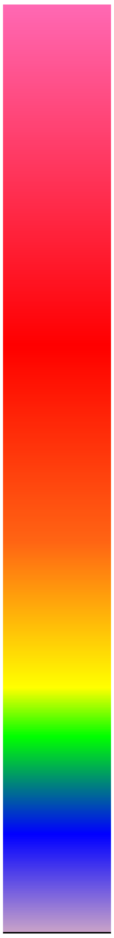

Figure 61

Appendix B - Evaluation form

Building inspection 1A, 1B, 1C, 1D, 1E, 1F, 1G

Look around and orientate yourself, compare the view in IR to the real world. Are the objects recognizable? Examine cold objects, hot objects and small temperature difference objects such as moist stains and fingerprints. Also look at scenes with large dynamic temperature spans.

Contrast

-5 -4 -3 -2 -1 0 1 2 3 4 5

Impossible to see what one is looking at.

Very small temperature differences are visible (such as moist stains).

Color to temperature

-5 -4 -3 -2 -1 0 1 2 3 4 5

Color & temperature feels completely disconnected.

Certain colors are always connected to certain temperature.

Intuitiveness

-5 -4 -3 -2 -1 0 1 2 3 4 5

Difficult to understand how to use.

Easy to understand how to use.

Food inspection 2A, 2B, 2C, 2D, 2E

Orientate yourself in room temperature and look into fridge, are the things you're looking at recognizable? Try to find objects in fridge that are too hot (or cold).

Recognizing objects

-5 -4 -3 -2 -1 0 1 2 3 4 5

Objects not recognized at all.

Objects recognized

Finding deviations

-5 -4 -3 -2 -1 0 1 2 3 4 5

Deviations not found.

Deviations are easy to find

Intuitiveness

-5 -4 -3 -2 -1 0 1 2 3 4 5

Difficult to understand how to use.

Easy to understand how to use

Appendix C - Camera specifications

Model name	FLIR A615
IR Resolution	640x480 pixels
FOCUS	Automatic or manual
Temperature range	-40 °C – 150 °C, 100 °C – 650 °C, 300 °C – 2000 °C
Accuracy	±2 °C
Emissivity correction	Variable 0.01 - 1
Ethernet image stream	16 bit 640x480 pixels at 60Hz

Table 22