computer graphics & vision

Inffeldgasse 16/2, A-8010 Graz

www.icg.tugraz.at

TU Graz

# Thermochromic Temperature Measurement: A cost-efficient alternative to thermal cameras

Thomas Nussbacher

*Institute of Computer Graphics and Vision*
*Graz University of Technology, Austria*

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***Clemens Arth, Philipp Fleck***
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Contact: Thomas Nussbacher, thomas.nussbacher@student.tugraz.at

## Abstract

*This work presents a cheaper alternative for measuring surface temperature without using thermal cameras or other expensive temperature measuring devices. We will make use of color changing pigment and a simple RGB webcam to get an estimated temperature value of a selected area in an image. We will take a closer look at the properties of different thermochromic pigments and how they can be applied to different surfaces. We will show how a calibration procedure is used to analyze the behavior of the pigment and form a connection between temperature and color, allowing us to estimate the current temperature.*

**Keywords:** *Temperature measurement, Thermochromism, Camera, Image Processing*

# 1 Introduction

In today's world, we need to measure surface temperatures for various reasons. Imagine needing to check how hot a machine is running or figure out if a building is experiencing heat loss. This is where modern technologies come in handy. One such technology is infrared thermography, which uses special sensors to measure the heat coming from surfaces without touching them. This helps us quickly and precisely know the surface temperature, making it useful for testing insulation efficiency of buildings, checking machines or other cases where energy gets lost in the form of heat. These modern methods help us to understand and deal with temperature changes in different places, to prevent things like overheating, energy loss and in the end prevent unnecessary expenses.

There exist several such infrared thermography devices like Infrared Thermometers and Pyrometers or Thermal Infrared Sensors. The probably most prominent one are Infrared Thermal Cameras. In contrast to RGB cameras, thermal cameras operate in the infrared spectrum, capturing the heat emitted by objects. While RGB cameras provide detailed color images, thermal cameras visualize temperature differences using grayscale or false color in combination with color maps. These devices also allow the detection of heat variations even in complete darkness.

Other devices like infrared thermometers typically measure the temperature of a specific point or area, offering a limited perspective. On the other hand, thermal cameras can capture thermal information across a wider scene, making them more suitable for applications like night vision, industrial inspections, and monitoring temperature-related issues.

One of the biggest downsides of thermal cameras is their price. In general, RGB cameras are more affordable compared to thermal cameras. RGB cameras have been widely used for many years, and the technology is mature, resulting in lower manufacturing costs. On the other hand, thermal cameras utilize more specialized technology and materials, which contributes to higher production costs. The sensors used in thermal cameras to detect heat emissions are more complex and less common than those used in RGB cameras. While the cost of thermal cameras has decreased over time with advancements in technology, they still tend to be more expensive than RGB cameras.

In scenarios requiring the coverage of a large surface area, the limited field of view of individual cameras requires the deployment of multiple devices. However, the use of thermal cameras for such purposes introduces a financial consideration. With thermal camera prices commencing at the upper hundreds, the cost associated with deploying several units could potentially surpass budgetary constraints.

In this work, we propose a cheap alternative for temperature monitoring without thermal cameras. The presented **estimation system** involves thermochromic paint, which is applied to surfaces. This way we are able to get visual feedback about the approximate temperature. Following a calibration process, where the properties of the paint are analyzed, a mere RGB camera becomes sufficient to derive an accurate estimation of the current temperature on the target surface.

With this estimation system, it is possible to measure surface temperatures, where thermal cameras can not be deployed. An example would be when the target surface is placed behind glass. It blocks infrared rays, and one would need special, more expensive alternatives like germanium glass. For our system this would not be a problem, since RGB camera sensors have no difficulties with such materials.

# 2 Chromism

Chromism is a fascinating property of certain materials, which refers to their capability to undergo a change in color in response to specific external stimuli [3]. This phenomenon adds a dynamic dimension to these materials, making them responsive to factors like light (pho-

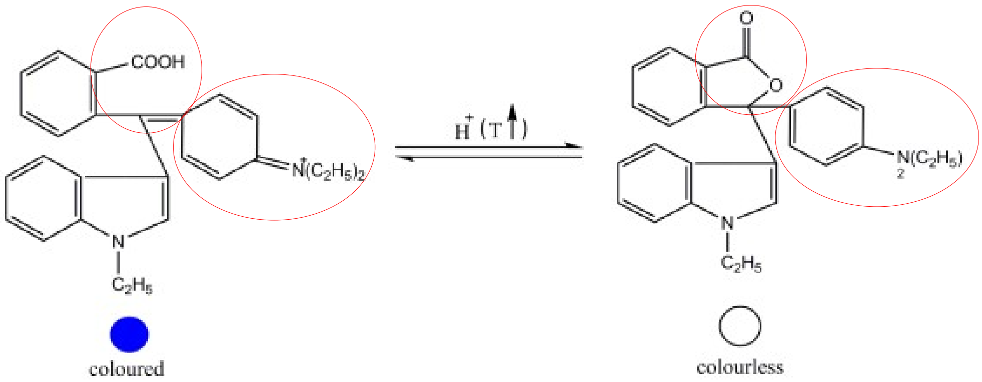


Figure 1: An illustration of how a blue thermochromic pigment changes its molecular structure when heated up. This causes a color change of the compound, and the pigment transitions from blue to colorless. Since this transformation is reversible, the compound changes back to its original structure and color when cooled down. This is an example for one of many of such pigments. Other compounds will look significantly different in regards to the molecular structure and its changes. The red cycles show the parts of the molecule that are affected by the temperature change. Image taken from [5].

tochromism), temperature (thermochromism), pH (holochromism), or other environmental conditions. The ability of a material to transition between different colors does not only find application for creating appealing and interactive entertainment products. It also serves a practical purpose in various fields. In the realm of chromic materials, thermochromism stands out as an interesting subset.

### 2.1 Thermochromism

Thermochromism is a chemical phenomenon, most commonly in the realm of organic chemistry. It refers to the property of certain compounds to change in color when exposed to alterations in temperature. The color change happens in a reversible manner and is limited to a specific temperature range. This property was first formally recognized in the late 1920s, with the simultaneous reports [2] on the thermochromic behavior of di-naphthospiran, a colorless compound that transformed into a blue-violet melt upon heating and reverted to its original state upon cooling. The term thermochromism includes a broad spectrum of compounds that undergo noticeable and reversible color shifts within specific temperature ranges. The mechanisms responsible for such phenomena are diverse and can be attributed to factors such as crystal structures or molecular transformations like ring opening and formation of free radicals. An illustration of such a transformation is shown in Figure 1.

Two primary types of materials exhibiting thermochromic properties are thermochromic liquid crystals and thermochromic leuco-dye pigments. Thermochromic liquid crystals are compounds that exhibit liquid crystal behavior. Liquid crystals are substances that have properties of both liquids and crystalline solids. The color change in thermochromic liquid crystals is a result of changes in their molecular alignment or order. As the temperature changes, the molecular order of the liquid crystals is altered, leading to a shift in the wavelength of light they absorb or reflect, resulting in a change in color. Thermochromic leuco dye pigments are composed of leuco dyes, which can change between states of colored and colorless. When exposed to temperatures above a certain threshold, they change from one state to the other. The color change in leuco dye pigments is driven by a reversible chemical reaction. When the temperature increases, the leuco dye undergoes a chemical transformation, resulting in a visible change in color. When cooled down, it changes back to its original state.

The color range of thermochromic liquid crystals is often limited to specific wavelengths associated with their molecular structure. Whereas leuco dye pigments can exhibit a broader range of colors, depending on the specific chemical composition of the dye. Both thermochromic liquid crystals and thermochromic leuco dye pigments offer unique advantages and are chosen based on the specific requirements of the application. The application descending from thermochromic behavior, which is used for this work, is the development of thermochromic paint. This innovative paint shows a temperature-dependent color change. This not only enhances the visual appeal of surfaces but also provides information about their current temperature.

Thermochromic paint has found applications in various fields. It is used in consumer products like mugs, toys, and clothing, adding an element of entertainment and surprise. Besides entertainment products, these pigments have also found application in various practical fields. As shown by Perez *et al.* [10], in the construction industry, thermochromic coatings on buildings or infrastructure could not only serve as a visual indicator of temperature-related changes, but potentially could help to improve the energy efficiency by regulating the absorbance of solar energy.

#### 2.1.1 Activation temperature

The activation temperature of thermochromic pigments refers to the specific temperature at which these pigments undergo their color change. Thermochromic pigments are designed to respond to changes in temperature by altering their color. When the temperature reaches or surpasses the activation temperature, the pigments exhibit a distinct color transformation. The activation temperature can vary depending on the specific formulation of the thermochromic compound and its intended application. It is important to mention that for most pigments, the transformation already starts before the respective activation temperature is reached. After this temperature threshold, it is guaranteed that the transformation is completed. In this temperature range, from the start of the transformation to fully completed, we are able to determine the exact surface temperature using our estimation system. Depending on the thermochromic compound and its formulation, this transition phase can happen in temperature ranges of 10°C up to 70°C. Although, for the majority of conventional pigments this range lies at the lower end.

## 3 Related Work

To gain a better understanding of the possibilities and limitations of thermochromic pigments, we start by examining several works that look deeper into real-world applications of these dynamic compounds. Understanding how thermochromic colors perform in practical scenarios is crucial for assessing their viability across various fields. Following this approach, we then turn our attention to works that research into the properties of these colors under specific circumstances. Analyzing the chemical and optical aspects of thermochromic pigments in diverse conditions helps to better predict their behavior and applicability. Finally, we explore an initial approach that utilizes thermochromism for temperature measurement.

### 3.1 Real world applications

#### 3.1.1 Thermochromic mortar

As mentioned earlier, Perez *et al.* [10] explore the development and characteristics of a reversible thermochromic mortar designed for the use as an external building coating. The used material is based on ordinary white Portland cement, featuring various additives, including commercial

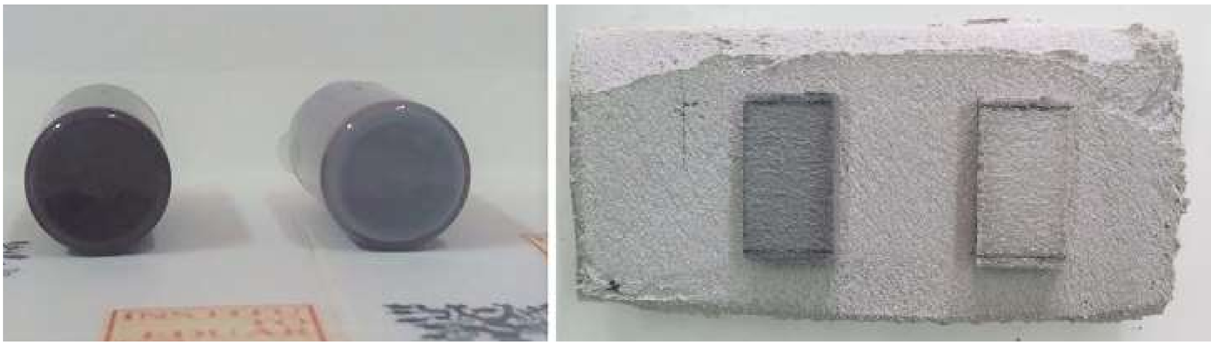

Figure 2: Color difference of Portland cement mixed with thermochromic pigment at different temperatures. Left: Difference of the thermochromic slurry at 8°C (left) and 50°C (right). Right: The finished mortar at the corresponding temperatures. Images taken from [10].

reversible thermochromic pigments. A closer chemical analysis confirms the proper integration of the pigments within the mortar and the stability of the resulting mixture.

The optical characterization reveals a dynamic response of the mortar to temperature changes. The color changing behavior of the resulting product is shown in Figure 2. According to the authors, the reflectance increased by up to 50% in the visible spectral range. The incorporated thermochromic pigment allows the material to transition from a dark to a light color, impacting solar absorbance. As a result, a 19% decrease in solar absorbance is achieved upon heating the mortar beyond its transition temperature, demonstrating its potential to enhance energy efficiency by reducing surface heating in warm conditions.

Regarding material properties, Perez *et al.* report positive results. In both fresh and hardened states, the thermochromic mortar shows desirable properties such as 100% water retention, plastic consistency, low bulk density, and suitable mechanical strength. This proves the suitability of the optimized composition to be used as an external building coating, showcasing promising characteristics for real-world applications. Yet Perez at al. emphasize the need for long-term stability and durability tests under various environmental conditions.

### 3.1.2 Thermochromic building coatings

Another approach regarding temperature regulation using thermochromism has been investigated by Civan *et al.* [1]. In their work, they developed intelligent thermochromic building coatings using a sol–gel spraying method with Methyltrimethoxysilane (MTEOS), tetraethoxysilane (TEOS), and thermochromic pigments. The coatings demonstrated the ability to switch between states of energy absorption and reflection in a reversible manner. Using the same principle as shown in the previous example, their work also aims to reduce the heating and cooling load of buildings. The sol-gel was heat-treated, and the resulting coatings demonstrated good temperature sensitivity and reversibility. Different analyses, such as XRD, FTIR, SEM, UV–VIS-NIR spectrophotometer, and DSC, affirmed the structural and thermochromic attributes of the coatings. The coatings displayed a reversible phase transition at 36.3 °C and 27.5 °C, making them suitable for creating a comfortable thermal environment in buildings. According to the authors, the coatings could contribute to urban microclimate development and energy conservation. This can be achieved by applying the coatings on windows of buildings or cars.

These two examples show the possibility of mixing thermochromic pigments with various substances, expanding the capabilities of the resulting products.

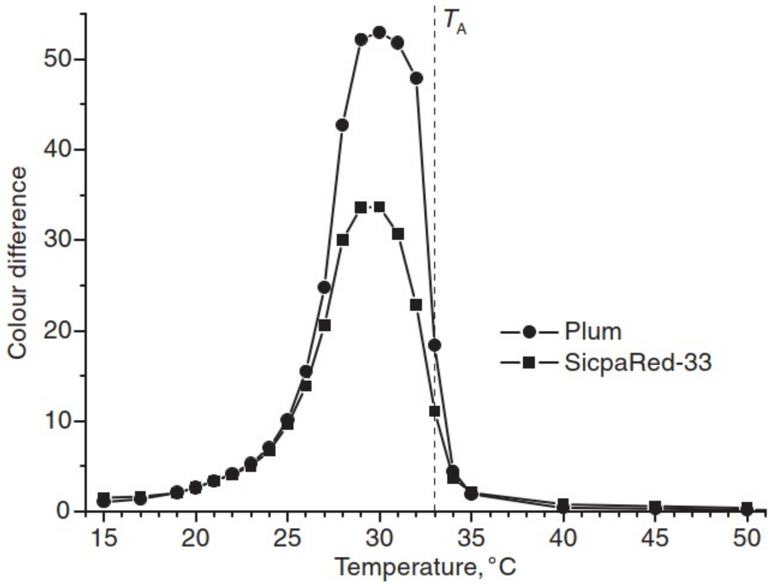


Figure 3: Color difference between heating up and cooling down of two conventional thermochromic inks. Although they have the same activation temperature $T_A$, they display unequal colors when comparing a pre-heated and pre-cooled state. This difference in appearance has its peak slightly below $T_A$, during the transition phase. Image taken from [8].

### 3.1.3 Other use cases

Another interesting real world application of thermochromic ink is smart product packaging [12]. By applying the ink on the packaging of temperature sensitive products like foods, visual abnormalities can act as an indicator for bad storage conditions. This eases the right handling of the products for both sellers and consumers.

The work of Peoples *et al.* [9] goes into detail about ideal substances for Thermochromic variable Emittance Coating (VECs) which should serve as a passive thermal management system for human spacecraft. The changing solar absorption and infrared emittance properties of Lanthanum Strontium Manganite (LSM) seem to be a promising candidate for this application. The transition temperature of LSM depends on the Lanthanum-to-Strontium ratio. Lets call this ratio x, then the chemical formula is $La_{1-x}Sr_xMnO3$. Using a ratio x=0.2, we get $La_{0.8}Sr_{0.2}MnO3$. $La_{0.8}Sr_{0.2}MnO3$ has an IR emittance of 0.5 for temperatures below -3°C. It increases over a temperature range of 70 degrees and saturates at 67°C with an IR emittance of 0.8. The tunability of LSM makes it an interesting choice for various special applications, like spacecraft coatings, to serve as a passive temperature management system.

## 3.2 Properties of thermochromic pigment

After exploring some examples of use cases for thermochromic materials, we also need to learn more about how such inks behave in different scenarios and conditions. Understanding the color changing behavior is necessary for our goals. For that we will learn about the differences of the color transition depending on the situation, and the usage of the pigments in combination with silicone and textiles.

#### 3.2.1 Dynamic colorimetric properties

In a study from Kulcar *et al.* [8] the authors performed a series of experiments with different thermochromatic inks. Among other things, they observed the behavior of the color change from heated to cooled, and vice versa. It involved the application of four different UV-curable thermochromic screen-printing inks, two from Coates Screen Inks GmbH (UV TCX R-31 and UV TCX B-31) and two from Sicpa (SicpaRed-33 and SicpaBlue-45). These inks contained leuco dye thermochromic pigments with varying activation temperatures. Thermochromic mixtures were prepared by combining two different inks. These include mixtures with similar activation temperatures and mixtures with different activation temperatures. The mixtures were applied to optical brightening agent (OBA)-free gloss coated paper using a screen-printer. Afterwards, the paper has been cured with ultraviolet light. The printed samples were subjected to heating and cooling cycles to observe color changes. To achieve controlled temperature changes, a thermostatic circulator was used that allows the water block surface to be heated or cooled. Using the CIELab color space, color differences were evaluated using the CIEDE2000 total color difference formula [11]. Kulcar *et al.* observed a hysteresis effect, where a function C[T] (color as a function of temperature) has the shape of a hysteresis loop. As shown in Figure 3, the colors were slightly different when in a cooling state in comparison to when the samples were heated up. For our goal of predicting temperatures only using color values, this is crucial information. Different colors at the same temperature, depending on the preheated state, would negatively affect the prediction accuracy of our estimation system. For this reason, our prediction mainly focus on the transition from a heated to a cooled state. We will discuss this limitation later on, and explore possible solutions from a software standpoint.

#### 3.2.2 Color stability in silicone

Kantola *et al.* [7] investigated the color stability of thermochromic pigment in a maxillofacial silicone elastomer. For a preparation step, the silicone was divided into three groups. Thermochromic pigment was added to two groups in concentrations of 0.2 wt% and 0.6 wt%, while the control group had no thermochromic pigment. Specimens were prepared using prefabricated stone molds, which went through polymerization for 2 hours at 90℃. After 20 days of storage in darkness at room temperature, baseline color measurements were taken. After that, specimens were exposed to UVA radiation for 6 hours daily. During this time, color measurements were performed using a spectrophotometer (Konica Minolta M-700d/600d) in the CIELAB color space.

The results were unsatisfactory. Only one 6-hour cycle of UV irradiation caused significant color changes in specimens containing thermochromic pigment. Already after 4 days of daily exposure, a saturation point was reached. UV irradiation had a significant effect on the color values of all specimens. This is a great negative example. It shows that not all substances are suitable for being used in combination with thermochromic pigments. With this information, we take silicone from the list of possible binding substances. Over the course our work, we will provide additional information about suiting binders that can be used in combinations with these special pigments.

#### 3.2.3 Application on textiles

Methods for application of thermochromic pigments on textiles were developed by Waseem [6]. In his work he used leuco dye and cholesteric liquid crystals, applying them on textiles using printing and extrusion.

To achieve a successful colorization of textiles using pigments, they are applied with some binder system on the surface of the fabrics. According to the author, the color strength of thermochromic pigments is less in comparison to other commercially available pigments. This is because of the lower amount of dye being present in the final formulation, typically about

2% in weight. To avoid pale shades, Waseem used a 30/70 ratio, with 30% of the weight in the coating being pigment. Since the goal of our estimation system is to work with as many surfaces as possible, including textiles, we will use similar ratios when painting pieces of fabric for our experiments. The downside is that the large quantity of pigment affects the feel and handle of the fabric.

As a binder, Waseem used Bricoprint Binder SD20E, Perapret PU New, Thermostar and LA-B 1096. In addition, a thickener (Magnaprint Clear M04) was used to enhance the consistency of the resulting printing pastes. It prevents pigment settling and ensures compatibility with the binders in the textile printing processes. As a printing fabric, 100% Cotton Duck PK44 White has been used because of its common usage.

The printing paste has been prepared using 10% binder, 4% thickener and the rest deionised, distilled water. This paste was then mixed with thermochromic pigment. The screen printing process involved engraving a 4cm-wide stripe design, which was then printed on a transparent sheet. A 77-mesh screen coated with Pure Coat 14 was prepared, dried, and exposed on an RA Smart exposure unit. After exposure, the screen was washed to remove uncured areas. A printing machine (Midi MDF31), with a 12.14mm diameter rod moved by a magnetic field, was used to apply the paste on the fabric. The printed fabric was then left for air drying, to later undergo curing in an oven with temperature and time variations. Results of color stability tests show, that samples which have been treated with higher temperatures also show less color strength. It is recommended to use lower treating temperatures (110°C) for maximum color strength.

### 3.3 Thermochromic temperature measurement

In a number of previous works ([1, 6, 9, 10, 12]), some interesting applications for thermochromic inks were presented. These also contained crucial information about the properties of these pigments and what substances do or do not work well when combined with such colors. Finally, we will study an initial approach of using thermochromism as a basis for a new temperature measurement method. Toriyama *et. al* [13] introduce a temperature measuring method using thermochromic liquid crystals (TLCs). As a measuring parameter they use the spectrum intensity of scattered light at a specific wavelength. For the measuring process, the hardware included an optical receiver, a halogen lamp with an infrared cut-off filter, and a water jacket. A cholesteric-type TLC sheet and type T thermocouples were placed on the water jacket's surface, which was constructed from a 20 mm thick aluminum plate. The water jacket's surface temperature was maintained by circulating temperature-controlled water through a thermochiller. The optical receiver, positioned vertically relative to the TLC sheet, was situated directly above the measuring point. The halogen lamp, tilted at a 45-degree angle against the surface normal of the TLC sheet, was positioned above it. An infrared cut-off filter was placed in front of the halogen lamp to prevent infrared heating of the TLC sheet. The scattered light's spectrum intensity was measured using a multi-channel spectroscope. The experiment took place in a dark enclosure to minimize external illumination disturbances. The TLC sheet's temperature varied from 20°C to 60°C in 1°C increments, surpassing the color change range of the TLC sheet (32–42°C). A scheme of the experimental setup is illustrated in Figure 4.

The results show that the peak in spectrum intensity shifts with temperature, enabling precise temperature determination. As a light source, a white LED is favoured over halogen lamps due to improved spectrum intensity measurement accuracy. Calibration against a white calibration plate allows for temperature interpretation based on the relative reflectance. Experiments using a monochrome camera show promising results, with a measurable temperature range (27–47°C) surpassing conventional TLC methods (32–42°C). This experiment proves that TLCs can be used for temperature measurement. In our work, we focus on thermochromic leuco dye pigments instead of TLCs, which allow the coverage of larger areas and a number of different surfaces. We conducted experiments where we test the limitations of these dyes regarding

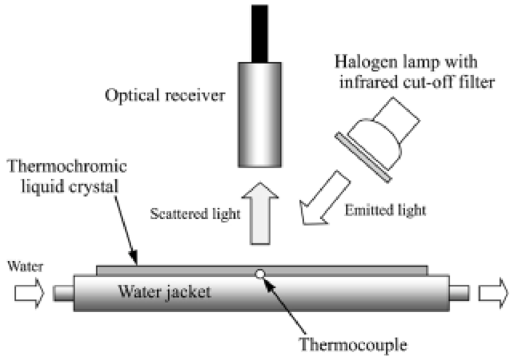


Figure 4: Scheme of the experimental setup to measure scattered light's spectrum intensity. A halogen lamp is used as a light source. On optical receiver allows to observe the scattered light from the thermochromic layer on top of the water jacket. Image taken from [13].

accuracy and performed optimization steps to improve the results.

### 3.4 Image color calibration

An important tool required for the successful implementation of our estimation system is color calibration. In an article from Haeghen *et al.* [4], a method is described for calibrating an imaging system by transforming an unknown color space to the well-known sRGB color space. The motivation of their work is to create an imaging system that can be used in the field of dermatology. With the ability of quantitative color and shape measurements, this system might be helpful for early detection of skin cancer. When working with commonly used color spaces like RGB or HSV, one has to keep in mind that the color space varies between imaging systems. For this reason, the authors introduce a method for calibrating an imaging system to transform to a device-independent color space. The calibration procedure involves a series of steps, including adjusting camera parameters, maximizing the dynamic range and achieving gray balance with the construction of a lookup-table. Afterwards, the images can be transformed to the sRGB color space. In our work, we also use a calibration procedure. In contrast to the just described method, where the output of different imaging devices can be transformed into a standardized color space, our method focuses on the calibration of one single camera. We try to get an understanding of the color changing behavior on surfaces, observed by a single device. It might be possible to combine these two approaches, so that our calibration is still valid when switching between cameras. However, this would exceed the scope of this work.

## 4 Experiments

In this section we go into detail about the series of experiments that have been conducted to better understand the behavior of different types of pigments in combination with several types of binding substances. The information obtained from the related work provides a good baseline on how to handle the pigments and what behavior can be expected. Due to the large range of different thermochromic pigments, and different approaches of the individual works, we first need to study the behavior of each pigment we want to work with. In addition, we take a closer look at how these pigments can be applied to different surfaces. Following that, a number of use cases for the examined pigments will be presented. One of which will be investigated further.

| Type/Name | Main Color | Secondary Color | Activation Temperature | Cost |
|---|---|---|---|---|
| Black Pigment | Black | Colorless | 50°C | ~1€/10g |
| Black Pigment | Black | Colorless | 65°C | ~1€/10g |
| Black Pigment | Black | Colorless | 70°C | ~1€/10g |
| Green Pigment | Green | Orange | 31°C | ~8€/10g |
| UR02 | Light Blue | Light Purple | 25-35°C | 2,50€/7ml |
| UR03 | Dark Blue | Light Purple | 25-35°C | 2,50€/7ml |
| UR05 | Purple | Light Purple | 25-35°C | 2,50€/7ml |
| UR06 | Dark Orange | Yellow | 25-35°C | 2,50€/7ml |
| UR011 | Gray | Light Pink | 25-35°C | 2,50€/7ml |
| UR012 | Dark Cyan | Light Cyan | 25-35°C | 2,50€/7ml |

Table 1: An overview of all pigments and colors that were part of the experiments. UR02-UR12 are the names of the colors from the thermochromic nail gel polish set (see Section 4.1.3).

## 4.1 Pigments

As previously mentioned, it's crucial to distinguish between thermochromic liquid crystals and thermochromic leuco dye pigments. For the scope of this work, we exclusively concentrate on leuco dye pigments due to their accessibility. Given our objective of developing a cost-effective alternative for large-area temperature measurement, these pigments align more closely with our goal. Now, let's delve into an overview of all the thermochromic pigments that underwent testing in our experimental phase. A short overview of all the pigments and colors can be found in Table 1.

### 4.1.1 Black to Transparent Pigment

The initial collection of pigments originates from "Xiamen Magic Color Technology Co., Ltd."[1]. The three pigments have a black surface color (while in cooled state) and transition to colorless upon heating. The activation temperatures cover 50°C, 65°C and 70°C. Depending on the desired color intensity, to cover a surface of $100cm^2$ about 5 grams of pigment are required. Waseem [6] suggests a mixing proportion 30% pigment and 70% binder.

### 4.1.2 Green to Orange Pigment

The next pigment is manufactured by "FILFEEL"[2]. This powder has a green appearance and has the ability to transition to a light orange color. With an activation temperature of only 31°C, it is possible to manipulate its color only using ones body temperature. Since the color difference between the cooled and heated state is rather small, it is less suited for our goal of accurately measuring temperatures using color values. For this reason the green pigment has primarily been used for textile testing applications and experiments with textile specific binders.

### 4.1.3 Thermochromic Nail Gel Polish

The third category of thermochromic colors to be tested is produced by "UR SUGAR"[3]. In contrast to the previous color options, these vials contain a UV-sensitive nail gel polish with built-in thermochromic features. The advantage of these formulations is the absence of required preparatory steps, eliminating the need for mixing it with a binding substance. However, in order to paint surfaces long-term, the gels require the use of an UV lamp for curing and hardening

[1] https://colorchangestuff.en.made-in-china.com/
[2] https://amzn.eu/d/cfMNElj
[3] https://amzn.eu/d/1qVSzGR

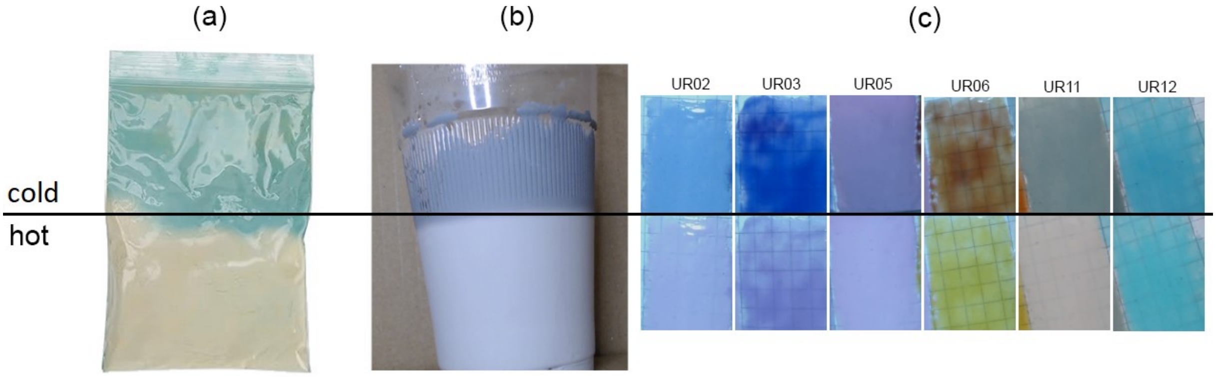


Figure 5: The thermochromic colors before and after the color transition. The top half shows the colors in a cooled state, the bottom half in a heated state. (a) Green pigment. (b) Black pigment (50°C) mixed with color lacquer. (c) Nail gel colors.

them. The color palette includes shades of gray, purple, pink, brown, olive-green, and cyan. Upon reaching the activation temperature of approximately 30°C, each gel undergoes a transition from a dark tone to a lighter tone of their respective color. For a visual representation of all the pigments and gels, refer to Figure 5.

## 4.2 Binding substances

At this stage of the experimental phase a suitable binding material has to be found. Since these powders do not stick to surfaces themselves, mixing them with a suitable binding substance is a crucial step when working with such colors. For our goal of creating a method for cheap, universal, large area temperature measurement, the ideal binder needs to fulfill a number of requirements. A description of the required characteristics can be found in Table 2.

To find such a binder, a series of test has been carried out. A range of potential substances and products has been tested in combination with the thermochromic pigments mentioned earlier. With the exception of the nail gel polish, which already comes in a ready-to-paint state. We will delve further into the specific characteristics of these gels and explore potential applications in subsequent phases of this work. We continue with a closer look at the potential binding substances for the thermochromic pigments.

**Resin** Resin is a viscous, sticky, and often clear substance derived from plant sap. It undergoes polymerization, forming a solid and durable material. Resins are widely used in various applications, including 3D printing, construction and coatings. They can be transparent or colored and are valued for their versatility, providing a durable and glossy finish when cured. With these characteristics, it seems to be a promising candidate for our purposes.

**Transparent nail polish** Nail polish is a cosmetic product applied to the nails to enhance their appearance. It typically consists of a colored liquid that dries to a hard, glossy finish. It comes in various colors, including transparent, and is applied using a brush. Although nail polish is mainly used for decorative purposes, it might also serve as a good binder for pigments.

**Color Fixative** A color fixative is a substance used to set or stabilize colors on various surfaces, preventing them from fading or bleeding. It is commonly employed in combination with textile color to preserve and protect colors on fabrics. Color fixatives are often applied as a spray or liquid and can enhance the longevity of pigments, dyes, or inks, helping to maintain the vibrancy

| Characteristic | Description |
|---|---|
| Color Absorption | The binder must effectively absorb the color of the thermochromic pigments to ensure accurate and vivid color changes. |
| Versatility | It should be applicable to a wide range of surfaces, allowing for flexibility in the use of the thermochromic pigments across various materials. |
| Textile Compatibility | The ability to combine the binder with textiles is crucial for creating thermochromic sheets, expanding the range of potential applications. |
| Homogeneous Mixing | The binder should seamlessly mix with the thermochromic powder to form a consistent and uniform mixture, ensuring even color distribution. |
| Color Neutrality | Ideally, the binder itself should have no color by itself, preventing any interference with the color changes induced by the thermochromic pigments. |
| High-Temperature Resistance | Given the nature of temperature-dependent color changes, the binder should be resistant to elevated temperatures to maintain stability during use. |
| Water Resistance | The binder should be resistant to water to prevent degradation or alteration of its properties when exposed to moisture. |
| Cost-Effectiveness | The binder should not be too expensive, so covering large surfaces is affordable. |
| Durability | The binder should contribute to the overall durability of the thermochromic system, ensuring long-lasting and reliable performance. |
| Accessibility | Availability of the binder should be widespread, ensuring effortless procurement. |

Table 2: A description of all the required characteristics that an ideal binder has to fulfill.

and integrity of the colors over time. With such promising features, color fixative has also been tested as a binder.

**Textile color** Textile color refers to a type of dye specifically formulated for coloring fabrics and textiles. These coloring agents are designed to provide a durable and vibrant color finish. Textile colors come in various forms, including dyes that penetrate the fibers and pigments that adhere to the surface. They are widely used in the textile industry for dyeing fabrics to achieve different colors and patterns. Using white textile color in combination with our thermochromic pigments might be a good approach for coloring textiles, upgrading their appearance with thermochromic capabilities.

**Textile color + color fixative** Since Textile colors are often used in combination with color fixative, we also investigated this combination to find a fitting binding substance.

**Color Lacquer** Color lacquer is a type of coating or finish that contains pigments or dyes and is applied to surfaces to provide color and a glossy appearance. Lacquers are typically clear or translucent and can be tinted with various colors. They are known for creating a smooth and shiny finish on surfaces, often used in woodworking, metalwork, and other applications where a polished appearance is desired. When used as a binder for pigments, color lacquer can serve as a medium to mix with and adhere to pigments, allowing for the creation of colored coatings or finishes. This is commonly employed in arts, crafts, and industrial applications where a colored and glossy finish is desired. In addition, the use of a lacquer helps to achieve durability. This might be the ideal candidate to be used with the thermochromic pigments.

A summary of testing the different binding substances including mixing ability and the final result can be found in Table 3.

### 4.3 Best Binder And Suitable Surfaces

As a result of the binder testing phase, two usable binding substances were found. For textile specific applications, the textile color has proven its usability by fulfilling most of the require-

| **Substance** | **Mixing ability** | **Final result** |
|---|---|---|
| Resin | Poor mixing ability. The resin does not bind with the pigment very well, a significant amount of time has to be invested to get a somewhat acceptable mixture. The color seems to be distributed unevenly. | After the mixture has been hardened, it does show thermochromic properties. We did notice a significant delay in reaction time (for the color change to occur) due to the fact that the hardened resin needs time to be heated up. In addition, heating up the resin emits an unpleasant smell. Moreover, the hardened substance breaks very easily when bent and therefore is not suitable for large-scare use. |
| Transparent nail polish | Excellent mixing ability. The nail polish almost immediately absorbs the colored pigment. | The mixture has a strong color. One disadvantage is that most nail polish vials do not contain more than 10ml and are relatively expensive. That aggravates the goal of large-scale coverage. |
| Color Fixative | This colorless liquid does show good mixing abilities. In comparison to nail polish, a lot more pigment is needed to get a similar color intensity. | Since this is a textile specific product, it has exclusively been tested with fabrics. A piece of 100% cotton fabric has been stained using the fixative-pigment mixture. Results show poor color intensity. The color does not stick to the fabric as expected. The fabric looses most of its color when being washed. |
| Textile Color | The thick consistency of this white paste makes it more difficult to mix with our pigment. Adding a view milliliter of water to the textile color improved the mixing capabilities. | The final mixture has a promising color intensity and a spreadable consistency. It can be used to paint textiles using a brush. Following that, the painted fabric needs to dry for 6 hours. Finally, it has to be exposed to 150°C for 8 minutes. After this process, the paint sticks to the fabric even after washing it. This textile color might be a suitable candidate as a binder for our thermochromic pigments. |
| Textile Color + Color Fixative | The color fixative can be used either to pre-treat the fabric before painting it or to mix it with the textile color instead of adding water. In combination, it resulted in good mixing capabilities. | It does not provide any benefits to additionally use color fixative. Adding some water to the textile color during the mixing process provides the same results. Also, there was no noticeable improvement regarding color intensity. |
| Color Lacquer | Similar to nail polish, the lacquer showed good mixing capabilities. Although the mixing process takes more time until all pigment particles are absorbed, the results still are convincing. Strong color and even distribution. | Due to the fact that this lacquer fulfills all of the required characteristics, this will be the final binding substance for the remaining of this work. It can be applied to almost any surface and can be bought relatively cheap, in large quantities for large-area coverage. |

Table 3: A summary of the test results of all the potential binders. The most promising results were found in Textile Color and Color Lacquer.

ments mentioned earlier. The main downside is the fact that the hardening process requires heat treatment at 150°C. The coloring process of the fabric also has been challenging due to the fact that the paint has a relatively thick consistency. Painting with a brush aggravated an even distribution and a smooth surface. For temperature measurement, this uneven surface will lead to difficulties. That is why color lacquer comes out as the best binder for our thermochromic pigments. This lacquer fulfills all the required characteristics for an ideal binder. Is has good binding capabilities, is resistant to environmental influences, is cheap and can be used on almost all types of surfaces. These include textile fabric, plastic, wood, metal, and many more.

For further experiments regarding temperature measurements, PET plastic cups were used due to their ability to store liquids. Heated water is used to investigate the color changing behavior of the pigments. The lacquer has proven as a good choice for the duration of our testing phase. However, one downside caught our attention. By repeatedly heating up the PET plastic, the high temperatures caused minimal deformations of the surface, invisible to the naked eye. This created small spots where the lacquer started to crumble, creating gaps in the paint layer. For long term use, this has to be kept in mind. However, this can be prevented by using materials which can handle high temperatures.

### 4.4 Testing Thermochromic Nail Polish

Besides traditional pigments, we also experimented with a set of nail gels with thermochromic properties. The set consists of six different colors. Unfortunately, the producer of these gels does not provide any information regarding temperature specifications. For this reason, our tests involve an analysis of the approximate activation temperature as well as the transition temperature range. This way we can determine whether these gels are suitable for our applications, and which of these colors work best. To better tell the colors apart, we will use the naming of the vials. The color palette includes six colors, UR02, UR03, UR05, UR06, UR11 and UR12. For a visual representation of the colors, refer to Figure 5. Using an experimental setup, we are able to generate temperature-color graphs for all six colors. The activation temperature and range is determined by analyzing the obtained graphs.

The results for all the colors were quite different. Due to the property of the gels, it has shown to be difficult to achieve an even distribution of the colors across a surface. While UR02, UR11 and UR12 seem to be easier to paint, the rest has been more sensitive to thickness variations, creating significant color differences. The data for the colors UR03, UR05 and UR06 is not usable, even after repeated testing iterations. Only the better ones can be analyzed in regards of temperature-color behavior. A visual representation of the data is shown in Figure 6. The gels start their color transition at about 15°C and saturate at an activation temperatures of 26-30°C. This gives a temperature range of 11-15°C, similar to the black pigments. The best results were achieved with UR12. The resulting graph seems promising to generate accurate estimation results.

The biggest downside of these gels is the uneven thickness distribution. Even when using the included brushes, it is almost impossible to paint the color evenly across the surface. In addition, even when creating multiple layers of paint, it seems that the gels still appear semi-transparent. This reduces the color strength. The bad distribution also affects the color changing process. Dependent on the color thickness, some spots register the temperature change later, which leads to a delayed transition. Another issue with the gels is the limited amount of compatible surfaces. While it sticks well to cardboard or fabric, it is unsuited for applications on plastic, glass and other similar surfaces. These surfaces do not absorb the color of the gels. This way the color is almost invisible, therefor unsuited for our applications in most cases.

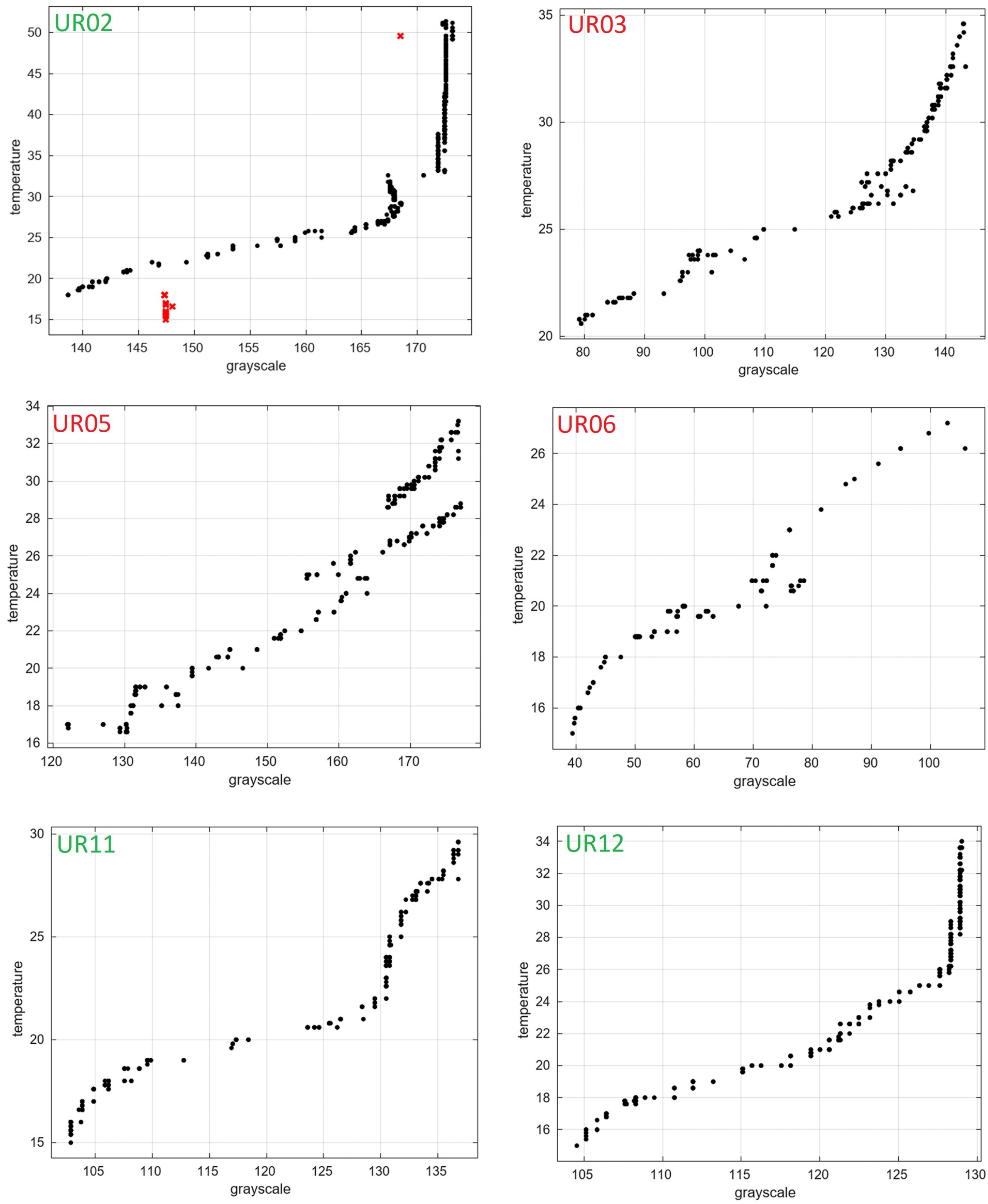


Figure 6: The temperature-grayscale graphs for the thermochromic colors of the nail gel polish set. Due to uneven thickness distribution the results are quite different. While UR03, UR05 and UR06 (red) seem to deliver unusable data, the remaining colors UR02, UR11 and UR12 (green) seem to be more promising candidates for an estimation.

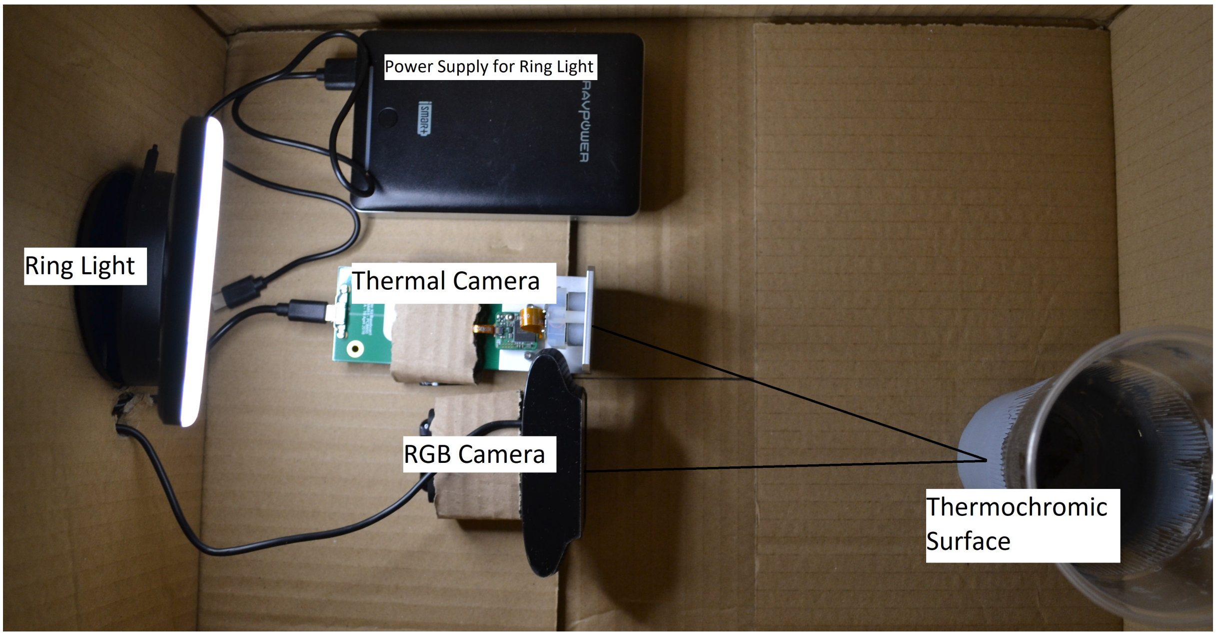


Figure 7: The setup used for the experiments regarding temperature estimation. Two cameras facing a thermochromic surface and a ring light to ensure sufficient lighting conditions.

### 4.5 Experimental Setup

Since we now collected all the required information that is needed regarding pigments, binder and surfaces, we are able to create an experimental setup. The goal of this setup is to be able to efficiently analyze the color changing behavior of the thermochromic surfaces we created. The final setup is structured as follows: Two cameras are placed side by side, both facing the colored surface. One RGB camera used to capture the color change, and one thermal camera the measure surface temperatures. As a surface, we used a regular plastic cup, painted with a mixture of pigment and color lacquer. For consistent measurements, the whole setup is mounted inside a sealable box. A white ring light serves as a constant light source. Now the color change can be analyzed using our calibration software. The whole setup is shown in Figure 7.

Following a calibration process, a color-temperature mapping will be created. Figure 6 shows the data collected for the nail gels, Figure 10 the data for the black pigment. This mapping is used to fit a curve. The obtained function is then used to estimate the temperature merely based on color values. More details about the software components can be found in Section 4.6.

#### 4.5.1 Hardware

Besides a computer to run software, only a number of hardware components will be needed. First, the surface that we need to surveil temperature wise, has to be painted with thermochromic ink. As mentioned in section 4.3, this is done either using textile color (to color fabric) or color lacquer. For the remaining tests, the outside of a plastic cup painted with the black 50°C pigment mentioned in section 4.1.1 serves as a thermochromic surface. This allows to heat up the pigment using hot water. The slow cooling down of the water enables to take measure points and simultaneously process image data. To analyze the color of the surface, a commercially available webcam is sufficient. For our experiments the Logitech C920 Pro HD webcam is used. The camera's sensor has a resolution of 3 Megapixel. It is capable of capturing photos and videos at a resolution of up to 1920x1080 and has a field of view of 78°. With the help of OpenCV[4]

[4]https://opencv.org/

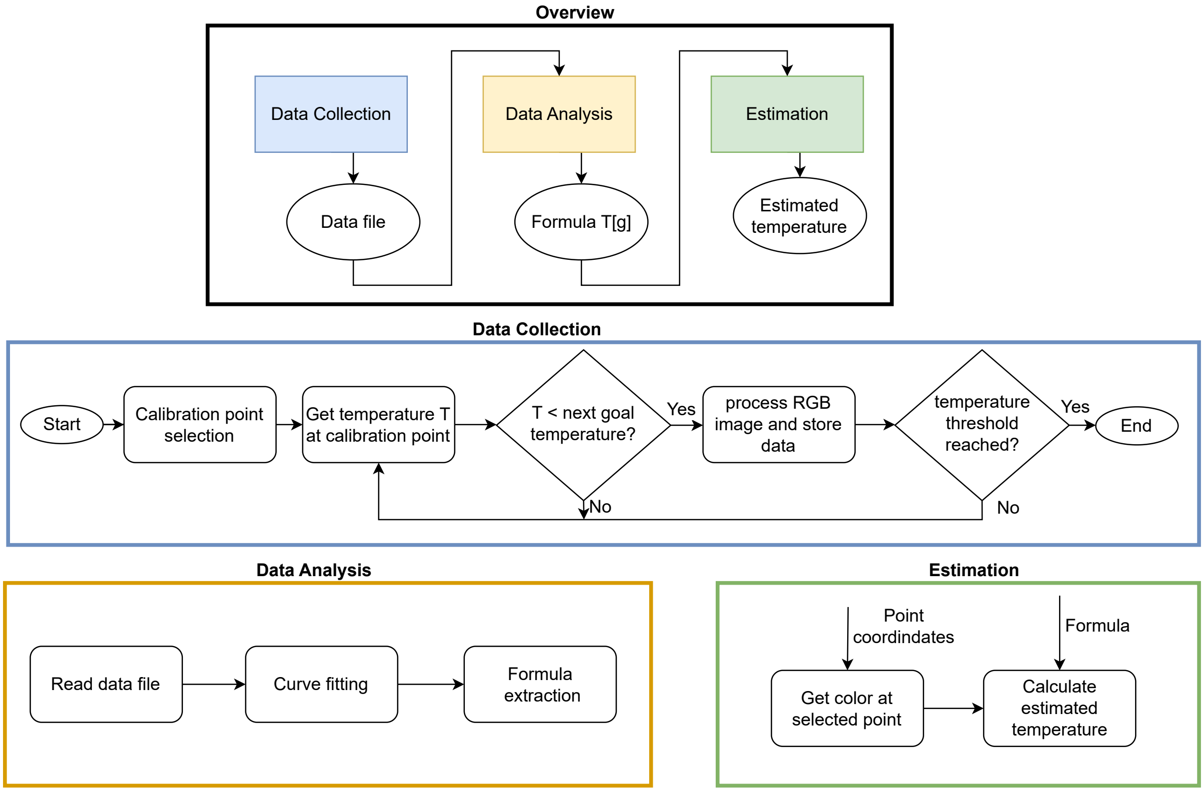


Figure 8: Overview of the software components. The data collection/calibration yields a data file, which is analyzed using Matlab. As a result, a formula T[g] (temperature with respect to grayscale value) is generated. This formula serves as input for the estimation software.

we are able to manually set camera parameters like focus, brightness, white-balance, contrast or saturation. This way it can be assured that the camera delivers consistent color values.

The calibration step requires to accurately measure the surface temperature of a selected point. Here, a thermal camera comes in use. For our experiments, we worked with the SEEK THERMAL S314SPX starter kit. This starter kit is a ready-to-use board including a thermal sensor. It is designed for an easy setup, minimizing time intensive preparation steps. The provided SDK from the manufacturer[5] includes code examples and serves as an entry point for developers. The sensor has a resolution of 320x240, with a 56° field of view.

## 4.6 Software

In this section we will go into detail about the software components used for our experiments, as well as the example software client for temperature surveillance. We will look into the control of the thermal camera, how the calibration procedure works, and finally how a graph is created to estimate the current temperature based on the color value. Python has been selected as the primary programming language for this work. It allows to quickly create window applications using the OpenCV Python package. While C++ might offer faster execution times and is also supported by the manufacturer of the thermal camera, Python is preferred due to minimal preparation requirements and the ability of swift development.

The software can be separated in three parts: data collection/calibration, data analysis and temperature estimation. An overview for the software components and how they are connected can be found in Figure 8.

[5]https://github.com/seekthermal

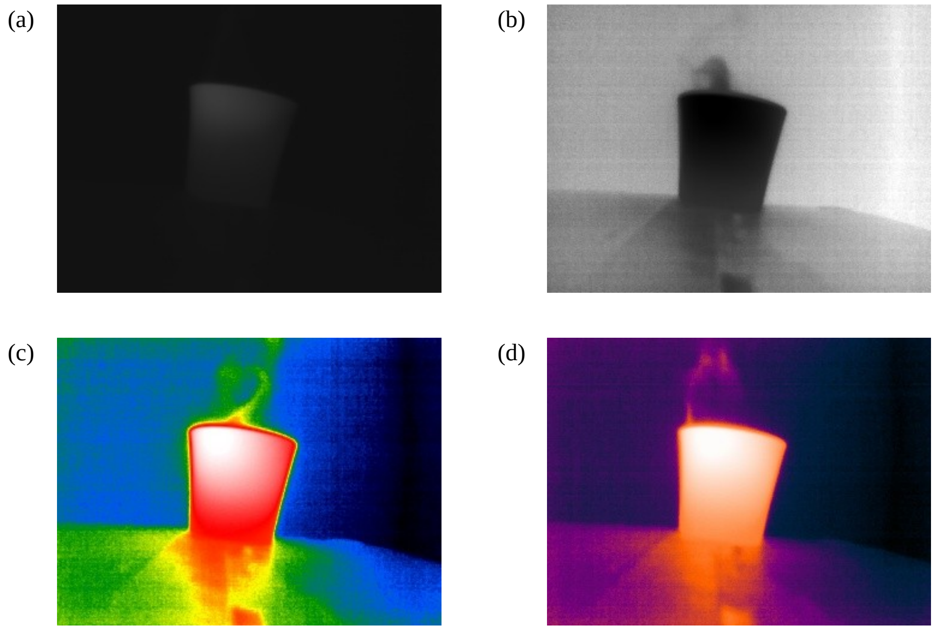


Figure 9: Selection of color maps included in the *seekthermal* Python package. (a) Grayscale image without a color map. (b) *BLACK_HOT* color map: Colorless representation by highlighting hot areas with dark pixels and cool areas with lighter pixels. (c) *SPECTRA* color map: One of the most common color maps used for thermal visualisation. It transitions from dark blue (cool) to light red (hot). (d) *TYRIAN* color map: Similar to *SPECTRA*, but limited to purple and orange color variations, with a transition from dark purple (cool) to light orange (hot).

### 4.6.1 Thermal camera control

For the calibration process, it is necessary to exactly know the temperature at a specific surface area. For this reason, a thermal camera is required during this stage. For clarification, after the calibration procedure no thermal camera is needed for the estimation. The thermal camera is connected to a Linux notebook using a USB Type A port. The SDK provided by the manufacturer is used to take care of the communication with the thermal device. The *SeekCameraManager* manages all the connected USB cameras. It is used to register events. The main camera events that can occur include *CONNECT*, *DISCONNECT* and *ERROR*. When a camera is connected, a *frame_available* event is registered and a new capture session is started. Now *frame_available* is fired every time a new frame from the camera is received. The information in each frame includes two 2-dimensional arrays. One stores the image, with each entry representing one pixel. The second array stores the temperature values at each pixel.

**Thermal image representation** Thermal images are commonly represented in a grayscale format. Applying a color map yields the familiar appearance of thermal images, highlighting temperature differences. The *seekcamera*-package from the manufacturer comes with its own collection of color maps. A selection of some of these color maps is presented in Figure 9. In order to obtain an accurate temperature value, it has to be derived from the grayscale image. For this, a grayscale-temperature mapping needs to be known. Usually, the required information is provided by the manufacturer. In this case, the *seekthermal* Python package does the calculations internally, and provides a ready-to-use temperature array for each received frame.

### 4.6.2 Calibration

The first step towards an RGB camera based temperature estimation is to perform the calibration procedure. The goal here is to obtain information about the color of the thermochromic surface at different temperatures. For this initial procedure and for testing purposes, a portable calibration setup has been created. It helps to perform tests in a controlled environment, ensuring undisturbed test runs. An illustration of this setup can be found in Figure 7. It consists of the RGB and the thermal camera (see Section 4.5.1), the cup coated with thermochromic paint, and a ring light. All these components are enclosed in a box, to shield them from external, inconsistent light sources. Our two cameras will be placed parallel at one end of the box, facing the other end. There, the cup with its thermochromic surface is fixated. On the wall behind the cameras, the ring light is attached.

The thermal camera serves as a temperature measurement device. In our case, it might seem that a simple thermometer for measuring the water temperature in the cup would be sufficient. However, since we need to know the temperature at the outside surface, this approach would not be accurate enough. This is due to the thin insulation layer created by the plastic, creating a temperature difference or delay.

The RGB camera is needed to observe the color change at the surface. It is important to use the same camera and conditions for the temperature estimation because a camera-specific calibration is performed in this first step. A different camera will have varying camera settings and might have a different sensor. This would yield deviant color values, making it unusable for the temperature estimation.

Before the calibration procedure starts, the cup has to be filled with water. The temperature must be above the activation temperature of the pigment. It is recommended to be in the range of (activation temperature + 20)°C, to make sure the pigment has fully transitioned to the heated state. This may vary when using different pigments. For pigments with an activation temperature below room temperature, other temperature regulation mechanisms must be used, such as a water jacket used for the experimental setup of Toriyama et. al [13]. Once the pigment is activated, one can start the calibration. When executing the *calibration.py* file, it is necessary to set the required parameters, capture interval and target temperature. The capture interval defines in which temperature intervals a color value is stored. Due to technical limitations of the thermal camera sensor, the smallest possible capture interval is 0.1 degrees. Although it might be better to to choose a slightly larger interval like 0.5 degrees due to the limited accuracy of the sensor. The second required parameter is the target temperature. It describes the approximate temperature at which the pigment has fully transitioned back to its original state. It serves as an end point for the program, causing its termination after reaching this temperature. We recommend to set this parameter to at least as low as (activation temperature - 20)°C, to make sure no information regarding the color transition of the pigment is lost.

After the calibration has been started, a connection with the two cameras is established. For the thermal camera we use the *seekcamera* Python interface. Using OpenCV's video capture functionality we are able to capture and read frames from the RGB camera. The two obtained frames are now cropped and placed side-by-side. On the bottom of the image, an information area displays current temperature and color information. The final image is displayed, so the two calibration points can be selected. That means for each of the two images displayed (thermal and RGB) a point can be selected. The calibration point of the thermal image marks the area of which the temperature needs to be known. Using a pre-calculated scaling factor, the selected coordinates directly point to the respective position in the temperature matrix received from the thermal camera. For a more accurate measurement, multiple temperature values surrounding the calibration point are used to smoothen the results. This is done by selecting a 49-neighbourhood (7x7 grid) around the point and calculating the mean temperature. For the user, to avoid confusion or uncertainty about the actual relevant pixels, the calibration points do approximately represent the size of the pixel neighborhood. The same procedure does apply

to the point selected in the image from the RGB camera. Instead of temperature values, here the mean RGB values are determined. The mean color is also displayed at the bottom of the output frame as a visual indicator for the user.
After both calibration points are selected, the actual calibration process is started. The current temperature is measured and a temperature threshold is set to (temperature - capture interval). The temperature at the calibration point is measured continuously. Each time it undercuts the threshold, all the required data is collected and the threshold is updated. Over the duration of the cool-down, the user interface is updated each time a noteworthy temperature change happens. With the text added to the bottom of the output images using OpenCV's text functionality, it is possible to track the progress. The program runs until the target temperature is reached and the calibration procedure is finished. The collected data includes the current temperature, color values and the grayscale value. In addition, all the output frames are saved as images in a separate folder, allowing a closer follow-up analysis of the entire procedure. The data obtained during the calibration is stored in a separate *DAT* file, making the follow-up data processing easier since this file extension allows to be opened as a table when using *Matlab*. In the next step, the grayscale values will be set in correlation to the temperature values, creating a color-temperature mapping.

### 4.6.3 Data Analysis

After a complete iteration of the calibration, we obtain a file containing all the information that is required to perform our estimation. There is additional data stored, e.g. hue, saturation, value (HSV) and the amount of red, green and blue (RGB) at the calibration point. It can be used for additional analysis in the future but will not be used by our estimation software. The focus lies on the temperature and the corresponding grayscale value. The grayscale value serves as a one-dimensional representation of the color change. Using Matlab, the data points are plotted. The temperature on the Y axis and the grayscale value on the X axis. The data distribution is analyzed using Matlab's Curve Fitting extension. This allows us to quickly generate functions using the data points as an input. By testing out different function types, the goal is to find one that best represents our data points. As a result, we obtain a function T[g] (temperature with respect to the grayscale value). An example of how such a function looks like can be found in Figure 10. Using a Matlab script, we are then able to automatically extract the function represented as text, and store it in a separate text file. This text file serves as the input for the estimation software.

### 4.6.4 Temperature Estimation Software

The final step is to use the information from the calibration and data analysis for the actual estimation, which is performed only using the RGB camera. The software behind the estimation is structured similar to the calibration. A live view of the camera is displayed, and a measure point can be selected by clicking on the desired spot in the image. The neighborhood of the corresponding pixel is selected which will be used to calculate the average color. This is done by taking the color information, which consists of the red, green and blue amount, and generate their mean values. A weighted sum finally builds the grayscale value. Since the software is programmed using Python, we make use of the SymPy Python library. This library has functions for symbolic mathematical operations. Is allows to generate symbolic expressions using formulas represented as strings. By providing a value, we are able to evaluate the expression. This way, when working with the input string that is our formula, providing a grayscale value will print an estimation of the current temperature, based on T[g]. An example frame of the estimation software output can be found in Figure 11. To make sure there are no estimations performed outside of the calibrated range, we implemented upper and lower limits. These limits mark a minimum and maximum grayscale value. When a value outside of this region occurs, we will

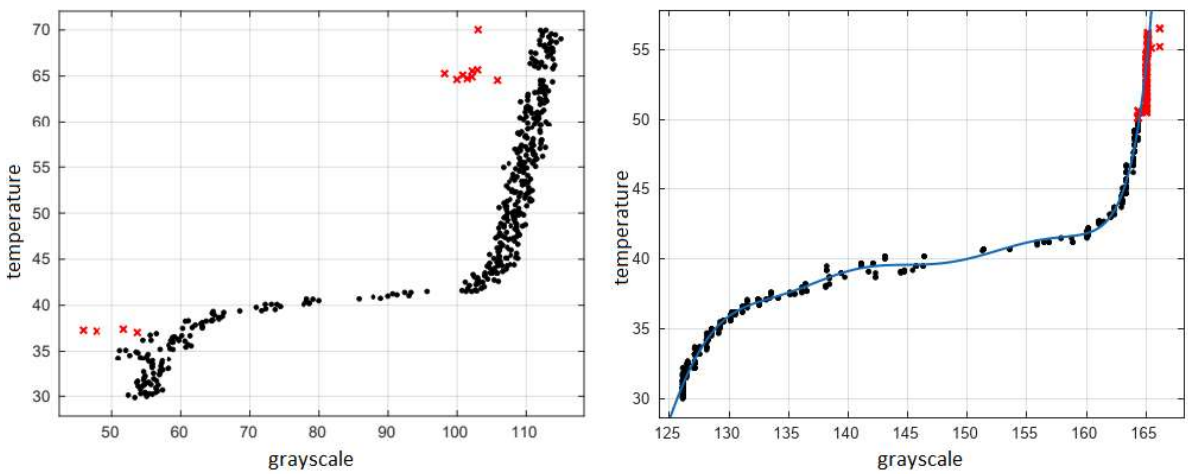


Figure 10: Example data points from different calibrations iterations of the 50°C black pigment. Each black dot represents one entry from the corresponding generated data file. Left: Before implementation of improvements. Right: After adding a constant light source and implementing frame averaging. Some points on the top right have been excluded (red cross), since in this area, the density of the data became unusable and would result in inaccurate estimation results. Here the resulting function T[g] is already generated, shown as a blue line. In this example, the function representing the data is a sum of multiple Gaussian functions.

perform no calculations. Instead, we indicate that this value is outside the valid region. Using the calculated temperatures at the corresponding borders, it is still possible to indicate whether the color lies below or above a certain temperature. Using the improved data shown in Figure 10 as an example, where the upper limit is set to 164, if the grayscale value is above this boundary, the program will display ">50°C". This way it is possible to detect if the pigment on the surface is currently in the cooled or heated state, even if the color is outside of the calibrated region. Table 4 shows example values comparing estimated and actual temperatures.

#### 4.6.5 Improvements

In order to get as accurate results as possible, some improvements have been implemented over the course of our experiments. The most noticeable differences were found after isolating the entire experimental setup from external lighting conditions. As shown in Figure 7, the setup

| **Mean RGB Value** | **Grayscale value** | **Estimated temperature output** | **Measured temperature** |
|---|---|---|---|
| 50°C Black Pigment | | | |
| R:144 G:173 B:198 | 167 | >47°C | 68°C |
| R:137 G:165 B:189 | 159 | 42°C | 44°C |
| R:111 G:147 B:173 | 139 | 39°C | 39°C |
| R:103 G:140 B:170 | 132 | <37°C | 30°C |
| UR12 | | | |
| R:0 G:179 B:204 | 128 | >25°C | 28°C |
| R:0 G:171 B:200 | 123 | 23°C | 23°C |
| R:0 G:153 B:194 | 112 | 18°C | 19°C |
| R:0 G:142 B:191 | 105 | <17°C | 16°C |

Table 4: A comparison of the estimation software output and the actual temperature. The data comes from test runs of the estimation software for the 50°C black pigment and the UR12 gel.

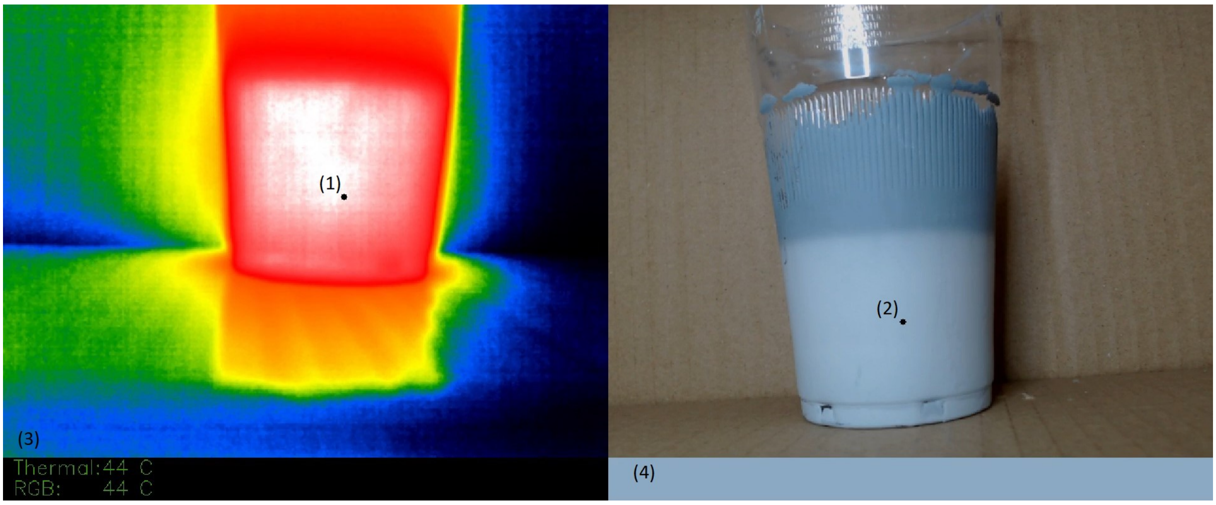


Figure 11: Example frame of the estimation software output. For verification of the estimation accuracy, the thermal camera is used as comparison. The captured frames of the thermal camera and the RGB camera can be seen. (1) Measurement point for thermal camera. (2) Measurement point for RGB camera. (3) Comparison of the measured temperature from the thermal camera and the calculated/estimated temperature using the RGB camera. (4) Representation of the mean color at the selected area of the RGB image, used for the estimation.

has been placed in a light isolated enclosure. A white ring light has been installed. It serves as a constant light source and provides ideal conditions for the RGB camera sensor. To prevent brightness fluctuations that might be caused by the battery of the ring light, we additionally included a power supply. For that, a simple mobile power bank is sufficient.

The second improvement was to implement frame averaging for the calibration procedure. This way we were able to reduce noise in the calibration images caused by the camera sensor. The implementation works as follows: Instead of taking the images only when data is stored, we continuously save frames in a frame buffer. This frame buffer is a ring buffer, where the last 20 frames are stored. A ring buffer of more than 20 entries would not further improve the noise reduction by noticeable amounts. The final frame is generated by accumulating these stored frames in the buffer and building the average. In the end we were able to improve the calibration accuracy by a satisfying amount. A comparison of the accuracy before and after the improvements were implemented can be found in Figure 10.

### 4.7 Use cases of pigments

Finally, we present some of the possible practical applications of thermochromic pigments, which have potential to be implemented in the future. This includes a use case for our estimation system.

**Temperature Regulation on Windows** As mentioned by Civian et. al [1], smart window coatings might be an energy-saving idea. By fine-tuning transparency in response to ambient conditions, these pigments contribute to the optimization of energy efficiency in buildings and cars. This adaptive feature helps to maintain a comfortable indoor environment while minimizing the need for artificial heating or cooling.

**Visual Indicators on Consumer Products and Electronics** Thermochromic pigments add both aesthetic appeal and practical functionality to consumer products such as electronic devices (PC cases, CPUs). The pigments change color based on temperature, offering a visual indicator of the device's thermal state. Beyond aesthetics, the visual indication serves as an important monitoring tool, allowing users to identify and address potential overheating issues quickly. This helps to prevent damage to electronic components and ensures optimal performance.

**Visual Indicators for Sensitivity Disorder Patients** In healthcare applications, thermochromic pigments can serve as visual assistance for people with conditions like polyneuropathy, sensitivity disorders, or dementia. As an example, using temperature-sensitive mugs can help to distinguish between cool and hot liquids, which can help to prevent burning injuries.

**Industrial Applications** The initial problem that led to the development of our estimation system comes from the industrial sector. Copper electrolysis is a process used to extract copper metal from copper ore or scrap copper. It involves passing an electric current through a solution containing copper ions. The copper ions gain electrons at the cathode, forming solid copper metal, while copper atoms at the anode lose electrons, dissolving into the electrolyte as copper ions. This process allows the purification and deposition of copper. During this procedure, unintended, low-resistance pathways can occur. These create shortcuts for the current to flow, bypassing the intended path through the electrolyte. The uncontrolled current flow wastes massive amounts of energy and can damage surrounding equipment. Usually, these malfunctions are only detected via increased energy consumption, which often is noticed only hours later. The short circuits also create a lot of heat. This is where thermal monitoring comes to use. Since putting a lot of temperature sensors into the electrolysis cell is not an option, surface temperature measurement has to be used. The most accurate solution would be to create a mesh of thermal cameras that covers the surface of the cells. Due to the fact that thermal cameras have a relatively small field of view and lower image resolutions in comparison to RGB cameras, multiple thermal cameras need to be installed to cover the entire area. Given that the prices of thermal cameras are several times higher than those of conventional cameras, from a financial perspective, opting for a more affordable alternative would indeed seem more attractive. For this reason, a cheap surface temperature measurement system using thermochromic pigment has been developed.

## 5 Results

To analyze the accuracy of our estimation system, we developed a program that allows to compare the estimated temperature to the actual temperature. With the help of the thermal camera used for the calibration, we were able to display live frames from both cameras. By selecting measurement points, similar to the calibration, we get a comparison of the actual and estimated temperature. This way we can evaluate the accuracy of the temperature estimation system. The evaluation has been done by performing multiple iterations of cooling down the thermochromic surface until the lower saturation point is reached. During this process, the actual and estimated temperature is compared. We were able to report positive results. The calculated temperature, that originated from the formula constructed after the calibration, was a correct estimation of the actual temperature during the whole cool-down phase, with a deviation of maximum 2°C. Before and after the effective temperature range was reached, we successfully determined whether the temperature lies above or below the defined upper and lower limit.

It is important to mention that all our experiments only investigated to cool-down phase of the dyes. As shown in Figure 3, there exists a difference in color appearance depending on the previous temperature state of the pigment. That means when using our method during a heat-up phase, the estimated temperature will be inaccurate. When the goal is to detect whether the temperature surpassed a certain threshold (heat-up), the system will work as intended when making sure the calibration is performed during the heat-up phase. In case of the need for accurate estimation in both directions, our system needs to be extended. This can be done by creating two temperature-color function, one for heat-up and one for cool-down. Via changes in the estimation software, it should be possible to detect the current temperature trend, and use the corresponding formula. However, more tests need to be done regarding this approach.

The range, in which the exact temperature can be calculated with the formula, depends on the properties of the used pigment. For the black pigments, we were able to create an effective range of 10°C. It is theoretically possible to extend this range by some degree, but this will lead to less accurate results with temperatures close to the saturation points. With such relatively small temperature ranges, our estimation system is only suited for specific applications, for example where a binary-like detection is desired. Nonetheless, with our work we demonstrated the potential of these pigments.

## 6 Conclusion

We have developed a method that allows to estimate the temperature on surfaces which have been painted with thermochromic pigment. Following experiments with different binders, we were able to make these pigments applicable to various types of surfaces. We developed software solutions for analyzing the color changing behavior of thermochromic leuco dye pigments. Following a calibration procedure, we successfully demonstrated the ability of our estimation system to predict temperatures only using an RGB camera. Although the measurement range is limited by the properties of the pigments, this method has the potential to replace thermal cameras in specific application fields.

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