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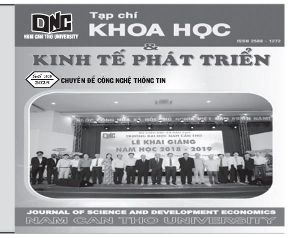

Research and development of hardware system for gemstone color identification device

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ABSTRACT

Color is a crucial factor in determining the value of a gemstone. However, establishing a standardized color system for different types of gemstones remains a significant challenge in the jewelry industry. Currently, color identification methods rely heavily on subjective color grading scales and manual assessment by experts. To address this issue, a new device called the GCIM (Gemstone color identification machine) has been developed. Its purpose is to digitize color measurements of gemstones and replace manual assessment, thereby promoting the advancement of the jewelry industry and improving efficiency and accuracy in gemstone appraisal processes. This study presents a new proposal for gemstone color classification and integrates hardware to enable gemstone color assessment based on this new system. This allows for a quantified measurement of gemstone color, providing a visual description. The GCIM device is currently undergoing the patent application process.

TÓM TẮT

Màu sắc là một trong số các tiêu chí để xác định giá trị của một viên đá quý. Hiện nay, việc xác định màu sắc chuẩn cho các loại đá quý vẫn là một thách thức lớn trong ngành công nghiệp kim hoàn. Phương pháp xác định hiện nay thường dựa trên các thang đo màu sắc và phụ thuộc vào sự đánh giá thủ công của các chuyên gia. Để giải quyết vấn đề này, một thiết bị mới được phát triển. Thiết bị GCIM (Gemstone color identification machine) đã được nghiên cứu và sản xuất, với mục tiêu lượng hoá các số đo của màu sắc trên đá quý, và dùng thiết bị đo đạc thay cho thủ công trong quá trình này, nhằm thúc *đẩy sự phát triển của ngành công nghiệp kim hoàn và giúp nâng cao hiệu suất và độ chính xác trong quá trình giám định đá quý. Trong nghiên cứu này, một đề xuất mới về việc phân loại màu đá quý được đưa ra cùng với sự tích hợp phần cứng cho phép đánh giá màu đá quý dựa trên hệ thống phân loại mới này, cho phép mô tả màu sắc của đá quý một cách trực quan dưới dạng lượng hoá đo đạc. Thiết bị GCIM đang trong quá trình xin cấp bằng sáng chế.*

1. INTRODUCTION

Color is one of the key factors in determining the value of a gemstone. Currently, determining the standard color for gemstones remains a major challenge in the jewelry industry. The existing methods rely mostly on color scales and manual assessment by experts. To address this issue, a new device called the Gemstone Color Identification Machine (GCIM) has been developed with the goal of digitizing color measurements on gemstones and replacing manual evaluation with this device, promoting the development of the jewelry industry and enhancing the efficiency and accuracy of gemstone evaluation. In this study, a new proposal for gemstone color classification is presented, along with hardware integration that enables gemstone color assessment based on this new classification system, allowing a digital representation of gemstone colors in a visually intuitive way. The GCIM device is currently undergoing the patent application process.

What is color? Why can humans perceive and distinguish different colors? In simple terms, human vision perceives color based on the recognition of the electromagnetic spectrum. However, color is not an intrinsic property of matter; rather, the ability of an object to reflect, absorb, emit, and interact with light determines the appearance of color. According to numerous studies, humans perceive color through cone cells, which primarily recognize light spectra in three main types. Color plays an important role in various fields, work, and daily life, adding value to art through aesthetics and visual satisfaction. Additionally, color theory is employed to harmonize and enhance aesthetics. However, there are many more colors than the human eye can perceive, which led to the 1969 study "Basic Color Terms" [2], describing that there are two "basic" color names distinguishing dark/cool from light/warm.

Human color perception is possible because of the ability of the eye to recognize the electromagnetic spectrum. The electromagnetic spectrum, also known as the collection of all types of electromagnetic radiation, is arranged by wavelength or frequency, including familiar types such as visible light, X-rays, radio waves, and infrared, as well as ultraviolet and gamma rays [1]. These types of radiation share the common concept of being defined by their wavelength (or frequency) and intensity. When a wavelength falls within a certain range, approximately 390 nm to 700 nm, the human eye can detect that light, known as "visible light" [3]. Most light sources emit light at various wavelengths, and the spectrum of each light source shows intensity at each wavelength.

Thomas Young's theory on color perception, like many of this pioneering scientist's achievements, remained unnoticed until Maxwell drew attention to it [11]. As another function of vision, color vision perceives differences in light created by various frequencies, independent of light intensity. As a crucial part of the complex visual system, color vision is controlled by neurons that react directly to light entering the eye. Photoreceptor cells send signals through layers of neurons, eventually transmitting them to the brain [7]. Research indicates that this function also appears in other animals, particularly primates, and may have evolved to facilitate hunting, food searching, and environmental danger detection.

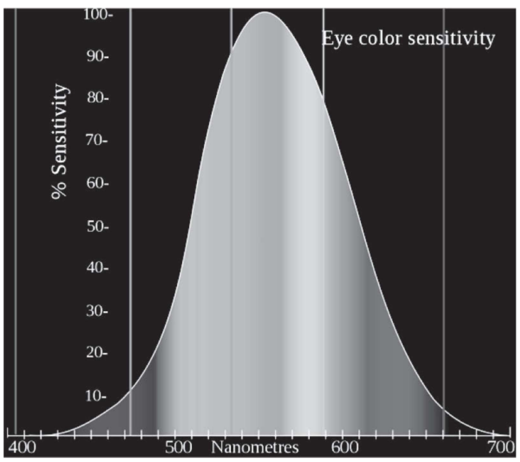

Figure 1. Relative brightness sensitivity of the human visual system by wavelength

Figure 1 shows the human visual system's brightness sensitivity across wavelengths, peaking at 550 nm in the green region. Color vision studies reveal that wavelength differences enable color distinction, with the highest contrast occurring in the green-yellow range. Larger variations appear in longer red and shorter blue wavelengths. The human eye can distinguish hundreds of colors, but when mixed with white light, the number of perceivable colors increases significantly.

In low or unstable light, known as scotopic vision [6], rod cells in the retina are responsible for light detection. In brighter conditions, photopic vision occurs, with cone cells sensitive to color. Between these conditions lies mesopic vision, where both rods and cones are active. Color perception changes from low to bright light [13]. The perception of "white" is formed by a mix of different wavelengths or only a few specific colors, such as red, green, and blue.

Color recognition starts with cone cells in the retina, which contain opsin proteins and respond to light. These cells are classified into short (S), medium (M), and long (L) types based on their peak sensitivity but do not directly correspond to specific colors. The brain processes these signals, reducing complex light wavelengths into three color components. Each cone cell follows the principle of invariance, meaning its response depends on the total light received. Together, the three cone types generate signals, known as tristimulus values, that shape color perception. [5]. For instance, it's impossible to stimulate only the medium-wavelength cone ("green" cone); other cones will inevitably be stimulated to some extent simultaneously. The entire set of tristimulus values defines the human color space. It's estimated that humans can distinguish around 10 million different colors [12].

In Table 1, cone and rod cells are unevenly distributed in the human eye. Cone cells are densely packed in the fovea and are sparse in the rest of the retina [10]. The cones respond differently to varying light wavelengths, and the brain synthesizes information from these cell types to produce different color perceptions. While color information is mainly gathered from the fovea area, there is also a capability to recognize color in peripheral vision, with the brain adjusting this information based on context and memory. Variations in opsin genes can result in various forms of color blindness, with the OPN1LW gene, which encodes opsin in L-cones, being the most common variation.

2. RESEARCH METHODS

Gemstones are rare minerals naturally formed through prolonged geological or biological processes. Due to their rarity and value, classifying gemstones has always been a meticulous profession requiring experience and skill. Most gemstones are classified by experts who personally measure their color based on established color systems, with the most notable systems being the GIA color system, the Munsell Color System, and the CIE Lab System.

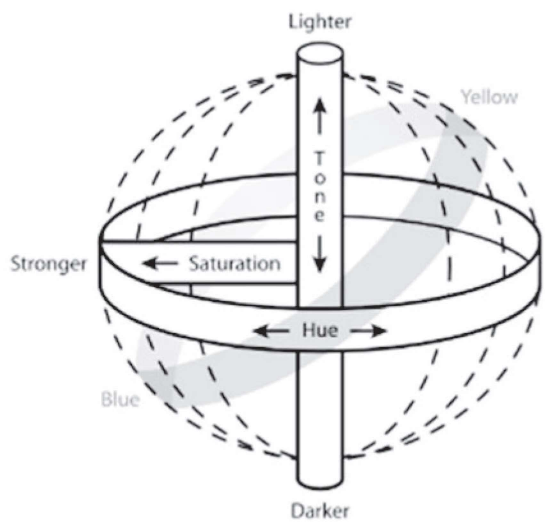

Figure 2. Illustration of color transformation axes

Numerous external factors, such as ambient light, viewing angle, cut, and polishing, can affect a gemstone's color (see in Figure 2). Currently, almost all measurement and evaluation steps rely on manual visual assessment.

2.1 GIA color system

The GIA Colored Diamond Color Reference Charts is a valuable tool for identifying and classifying the colors of colored diamonds. The chart includes color grades and descriptions for the most common colors of diamonds. Diamond color classification is performed by placing them on a non-reflective white plastic tray and assessing their color from a top-down view only. An observation box is used to create a separate environment and shield the diamonds from external light, ensuring a consistent color evaluation. For accurate color assessment, observers are periodically tested to ensure normal color vision. Once a diamond's primary color is determined, it is compared to known color samples in the color space under the same lighting conditions. The goal of comparison is not to select a specific reference sample but to establish a color range for the graded diamond [4]. Each color element of the diamond, including hue, brightness, and saturation, is determined and evaluated.

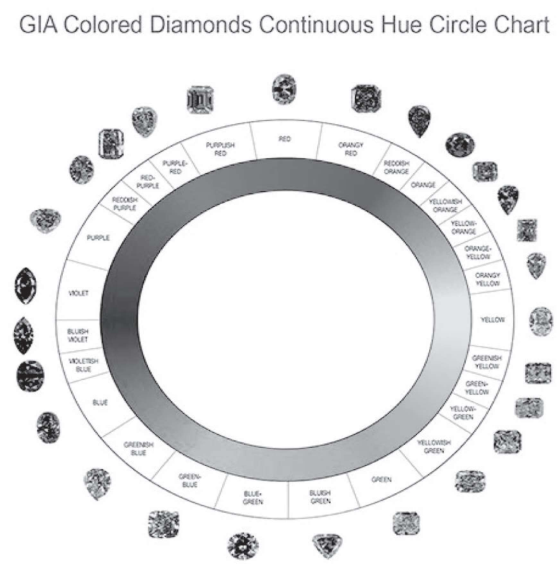

Figure 3. GIA's gemstone color wheel chart

The color wheel in Figure 3 shows each of the 27 colors GIA uses to describe different colored diamonds. Examples are reproduced at high saturation for each color. Each color reaches maximum saturation at different brightness levels, as shown in the samples (for instance, yellow is brighter than blue). The gray band on the left model also illustrates the overall placement of samples as they transition through the color wheel. Additionally, the GIA clearly defines color grading and color description standards in Table 2 and Table 3.

Table 2. Color grades

Fancy light	Subtle, delicate color
Fancy	Clear, recognizable color
Fancy intense	Deep, vibrant color
Fancy vivid	Extremely vivid and intense color

Table 3. Detailed color descriptions

Pink	Light pink, pink, deep pink, fuchsia
Blue	Light blue, blue, navy, deep blue
Yellow	Light yellow, yellow, yellow-orange, yellow-brown
Brown	Light brown, brown, dark brown, black-brown
Orange	Light orange, orange, burnt orange
Green	Light green, green, dark green
Purple	Light purple, purple, deep purple, lavender

2.2 Munsell color system

Developed by Albert Henry Munsell in the early 20th century, the Munsell System plays a significant role in scientifically describing and classifying colors. While previous color order systems arranged colors in a three-dimensional color block of some form, Munsell was the first to separate color, value, and chroma into independent and perceptually uniform dimensions, and he was also the first to illustrate colors systematically in three-dimensional space (Kuehni, 2001) [8].

The system is based on three main elements:

Hue: The position of the color on the color wheel, defined by an angle relative to the red point. The Munsell System includes 10 main hues: red, orange, yellow, green, blue, indigo, violet, pink, brown, and gray.

Value: The lightness or darkness of a color, measured on a scale from 0 (black) to 10 (white).

Chroma: The purity of a color, measured on a scale from 0 (gray) to 12 (most vibrant color).

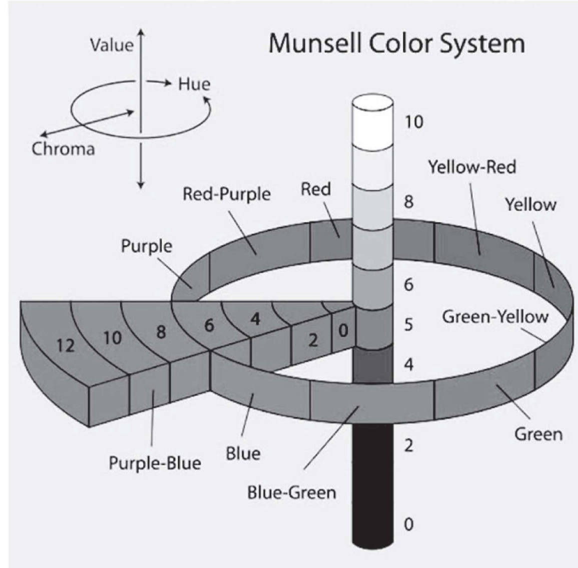

Figure 4. Munsell color system

The Munsell system (see in Fig 4.) is represented by a visually cylindrical color space, with hues arranged in a circle, brightness represented by the vertical axis, and saturation represented by the radius. Each horizontal Munsell circle is divided into five primary colors: Red, Yellow, Green, Blue, and Purple, along with five intermediate colors (e.g., YR) located between adjacent primary colors.

The Munsell system uses these three elements to create a cylindrical color space. Hues are arranged in a circle, brightness is represented by the vertical axis, and saturation is represented by the radius. Each color is defined by its position in this color space. For example, a bright red color with a hue of R, brightness of 5/, and saturation of /12 is denoted as R 5/12.

2.3 CIE lab color measurement system

The CIE Lab Color System (CIELAB) is a color space developed by the International Commission on Illumination (CIE) in 1976. This system is based on the human eye's ability to perceive colors and is widely used in science, engineering, and design [9].

The basic components of the CIE Lab System include three main factors:

- L* (Lightness): Represents the brightness level of the color.
- a* (Red-Green Axis): Determines the position on the red-green axis of the color.
- b* (Yellow-Blue Axis): Determines the position on the yellow-blue axis of the color.

This system uses a nonlinear scale to describe brightness and hue, better aligning with how the human eye perceives colors. Additionally, it is designed to have uniformity, meaning the distance between color points on the Lab chart corresponds to perceived color differences.

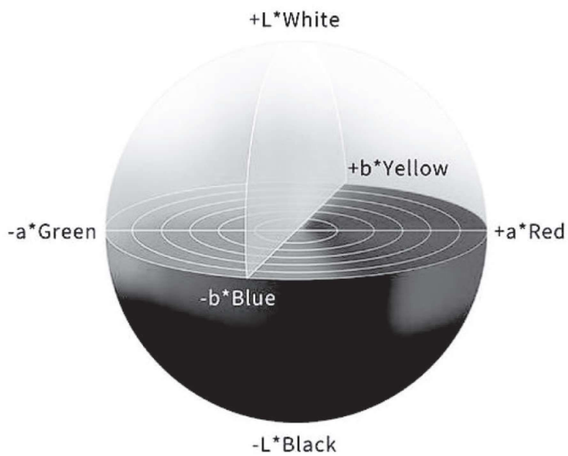

Figure 5. CIE-Lab color space

The CIE Lab System is widely used in science, engineering, and design for its accuracy and uniformity, despite some complexity and cost. It provides quick and easy color identification by comparing gemstones to a standardized blue color chart under white light. However, factors like light quality, user sensitivity, and experience can affect accuracy. Additionally, the system's block color space makes precise gemstone color naming difficult.

3. RESULTS AND DISCUSSION

3.1 GCIM

Based on concepts from the Color Wheel, the machine uses a color spectrum to classify the color of the sample. The color spectrum is divided into 360 color intervals on a circular display corresponding sequentially from 1 to 360 degrees. Each color interval has a corresponding RGB value. The machine selects 7 standard color intervals for red, orange, yellow, green, blue, indigo, and violet. For example, the standard interval for red is (R: 100 to 200; G: 20 to 70; B: 10 to 100). At each pixel of the image, if that pixel falls within the interval for color X, then it is added to the total pixel count for that interval:

- S (color X) = total pixels within color interval X in the image
- T = total pixels in the entire image
- Percentage (%) = S (color)*100/ T

Figure 6. Color space

In Figure 6, this is a color wheel that displays the color spectrum and the color detail of each interval within the spectrum. The color spectrum is shown as a circular diagram divided into 360 color intervals (1 degree = 256/360 computer color units). For example, the color interval for Red 1 is (R: 100 to 200; G: 20 to 70; B: 10 to 100). Each color interval has a corresponding RGB color. The machine will mark the 7 standard color intervals with large dots and display the color name next to them. The machine calculates each interval's unit by taking the total color degree of the pixels within that interval. For each pixel in the image, if that pixel belongs to the interval of color x within the standard color X, then:

- Deviation (1):

$$d(\text{color interval x, standard color X}) = |\text{interval degree x} - \text{standard color degree X}|$$

- Total color degree of standard color X (2):

$$\text{Ex} = (360\text{x total pixels of standard color X total pixels of the image})$$

- Total color degree of non-standard color (3):

$$\text{Ex} = [(360 - d(\text{color interval x, standard color X}) \text{ x Total pixels}$$

The machine displays the color degree of each color interval beneath the color spectrum. The detailed color degree of each interval indicates the distribution level of that color in the gemstone.

3.2 Hardware system design of the device

Today, the collection and appraisal of gemstones in the market are facing significant challenges. This process is not only costly but also requires precision and professionalism to ensure the actual quality and value of gemstones. The ability to recognize colors, transparency, and other characteristics of gemstones requires skill and long-term experience from appraisal experts.

Figure 7. Actual image of the device

The gemstone color identification machine is designed with many advanced features. Starting with the hardware, the device includes a manually designed circuit board connected to components for gemstone color analysis. This circuit then analyzes the color and returns results through a display screen and outputs a report via a USB port. Additionally, the machine is equipped with camera lift axes (forward/backward/left/right) and adjustable camera focus.

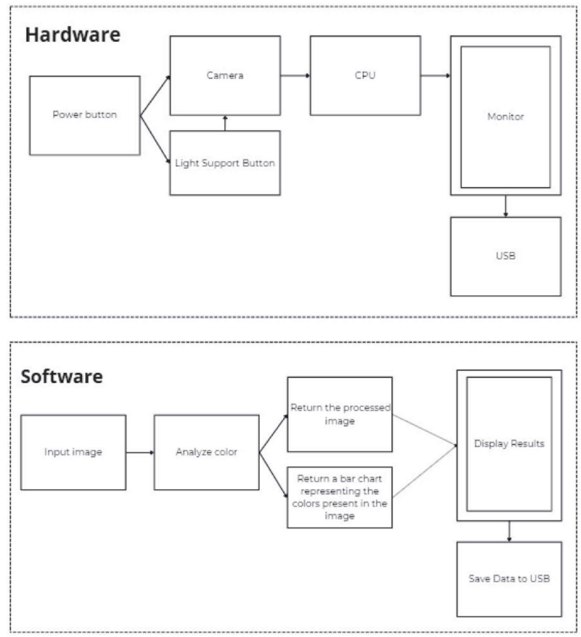

Figure 8. Hardware & software block diagram

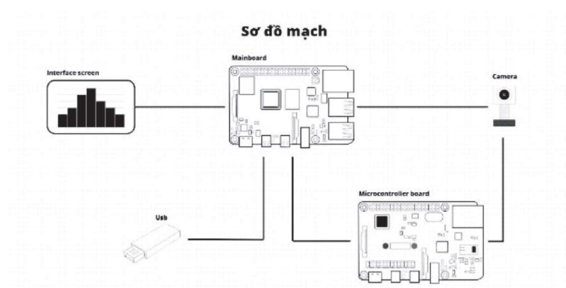

Figure 9. Processing schematic

Figure 8 depicts the integration of hardware and software components, illustrating their interactions for system functionality. Fig 9. shows the data flow through processing modules, highlighting key transformation steps from input to output.

The presence of the USB port allows users to quickly and conveniently extract data, facilitating later data processing. This optimizes the workflow and enhances the system's efficiency, reflecting a focus on convenience and effectiveness in AGC's design.

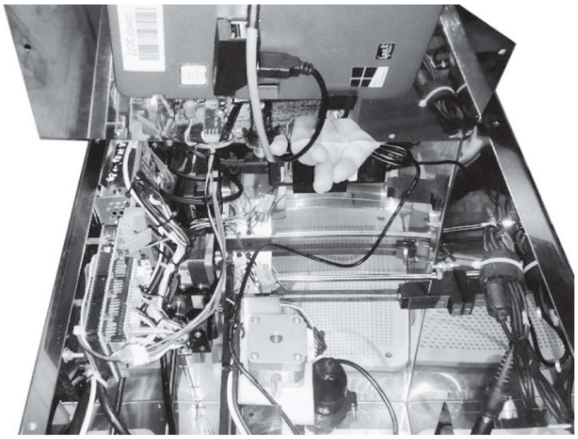

Figure 10. Internal details of the color identification machine

Figure 10 details the internal structure and components of the color identification machine, showcasing its functional arrangement. The AGC screen displays crucial information, such as object images, processing logs, processed images, color charts, and particularly, a new circular color space specifically developed. This provides an easy and convenient user experience and enhances the ability to analyze and understand the gemstones being processed.

4. CONCLUSION

In this study, foundational theoretical concepts on the significance of color in classifying gemstones were established, providing the basis for a device allowing an automated color identification machine to address this challenge. The Gemstone Color Identification Machine (GCIM) aims to advance the jewelry industry and improve efficiency in gemstone classification. This machine not only identifies gemstone colors but also automatically categorizes colors based on a new color space system better suited for describing gemstone colors. This development supports accurate product quality assessment for artisans and collectors and assists in documenting artifact colors in archaeology and related research fields. The GCIM devise is currently under evaluation for patent application.

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