Analysis of Birefringent Materials to Create Static Polarized Color Patterns for Visible Light Indoor Positioning

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Abstract

Visible Light Positioning (VLP) is an emerging field of research with several possible application. While most state-of-the-art VLP systems work with active modulation of light (switching lights on/off rapidly), this poses issues such as the flickering problem and excessive power consumption. In contrast, passive modulation of light (twisting/bending of light), with the properties of polarizers and birefringent materials, allows cost-effective modulation. This paper analyzes two birefringent materials - plastic (cling-wrap) and transparent adhesive tape - to test them for their usability in a visible light positioning system, in particular, the visibility range, hue-orientation mapping, and ambient light interference. These materials allow to create color patterns visible only to a camera. The patterns can encode data about identifiers of light anchors, while the color detected can be used to find the orientation of the receiver. It was observed that transparent adhesive tape gave much more reliable results, with a step-pattern-like hue-orientation mapping, and low errors (± 5) on the hue value detected in the range of 30-250 cm from the light anchor, making it ideal for VLP.

1 Introduction

Indoor positioning systems are a promising area of technology in the near future, with applications in various industries. This includes - supermarkets, retails stores, offices, automated car-parking garages, warehouses, etc. Given the widespread use of mobile devices and their ability to communicate wirelessly, a common choice to implement such a system is wireless communication channels such as Radio Frequencies (RF) [5; 16].

However, there are two major drawbacks of using the RF spectrum. Firstly, RF suffers from multi-path propagation. This means that at any given signal strength/intensity, two or more locations can be pinpointed as its source of origin. For example, in Figure 1, at -105 dBm (the red line), five different points (intersections) could have been the origin of this signal. Secondly, the RF bandwidth is starting to get overcrowded - its applications ranging from Wi-Fi access points to Cellular and Bluetooth. This mandates the need to explore a different range of bandwidth - in particular, Visible Light.

Visible Light Communication (VLC) provides several benefits compared to RF, particularly for Indoor Positioning. It is similar to communicating with a flashlight at night. Figure 2 imitates the line-of-sight propagation of light making it possible to pinpoint a particular distance/source based on the intensity of light received. For example, at an intensity of 10 Lux (the red line), the source must be at a distance of about 60 centimeters. This solves the multi-path propagation problem of RF. This also allows VLC to provide a higher degree of security since it is difficult to intercept any data being transmitted outside of line-of-sight. Additionally, VLC is a relatively new technology, owing to which the Visible Light spectrum is largely untouched.

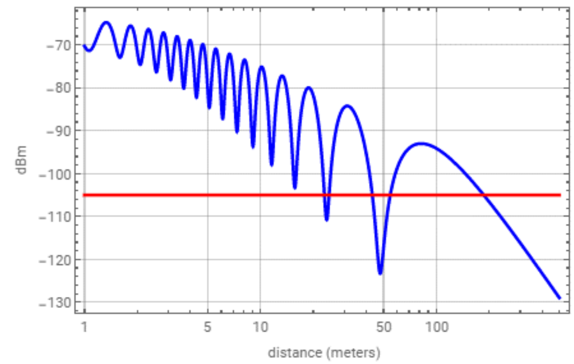

Figure 1: Multi-path propagation of RF signal - at any given intensity (dBm) multiple points (Distances) can be the source of this signal. [4]

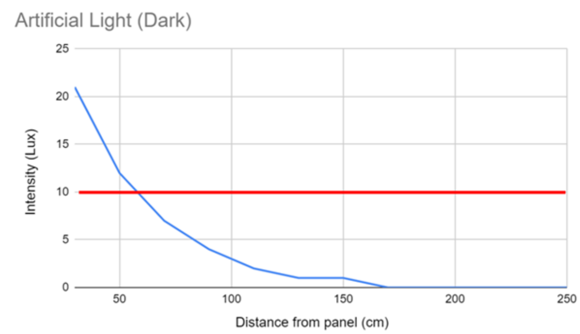

Figure 2: Line of Sight propagation of Visible Light recorded in a dark room - it is possible to discern a fairly accurate distance based on the light intensity (lux).

Visible Light Positioning (VLP) systems have four components - a transmitter, a receiver, a modulation scheme to allow communication between the transmitter and receiver, and a localization scheme to position the receiver. Modulation and localization schemes that allow for light weight transmitters and/or receivers are desirable. Current research in Visible Light Positioning (VLP) systems showcases several different modulation schemes which can be divided into two categories - Active and Passive.

Active modulation schemes involve the rapid switching on/off of lights. However, it can lead to the Flickering Problem - when the frequency of the switching is too low, it is visible to the human eye and can have undesirable health effects. Additionally, turning on a light source (LEDs for example) is power-consuming and at higher frequencies of switching on/off lights, the power consumption would be very high.

Passive modulation is the twisting/bending/dispersing of light and can be done by a combination of linear polarizers, which allow light to oscillate in only one direction, and birefringent materials, which refract an incident light in two different directions. By placing the birefringent material between two polarizers in front of a light source, a color pattern can be created to encode data, and capture/decode it using a camera. Figure 3 shows an example of such a pattern created with transparent adhesive tape.

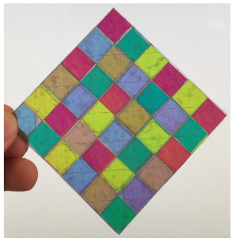

Figure 3: Grid-pattern made from transparent adhesive tapes placed between two polarizers [12]

In effect, this static color pattern can be used to transmit data about the location of the transmitters (also called *light anchors*), to position the receiver. The combination of a polarizer with a birefringent material form a sort of tag (like a QR code) that can be placed in front of a light source, either natural or artificial, to communicate identifiers for these light anchors. The color pattern will only be visible to a camera with a second polarizer. Figure 4 shows such an indoor positioning system which would use existing lighting infrastructure to position the receiver.

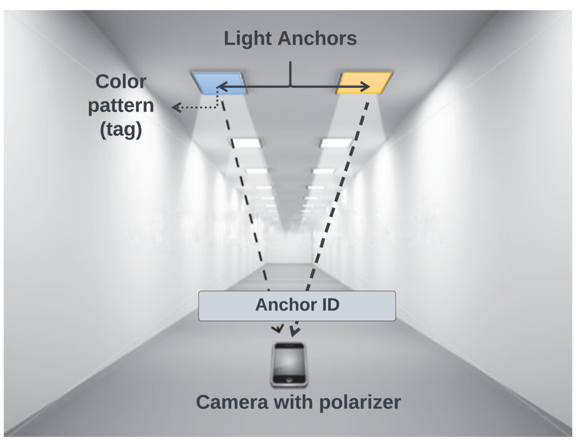

Figure 4: Visible Light Positioning system, with existing lighting infrastructure as transmitters, and smartphones as receivers. [3]

Static color patterns imply that there is zero power consumption. Additionally, polarizers and birefringent materials are readily and cheaply available. However, there is lack of evidence as to why transparent adhesive tape is the preferred birefringent material of choice to create static patterns [7; 12]. This paper analyzes two birefringent materials - PVC (plastic/cling-wrap) and transparent adhesive tape. These materials can be used to create a grid-like color pattern [12] which is ideal to communicate the identifiers of light anchors for easy localization (as seen in Figure 3).

The two materials are tested for their visibility range in dark and ambient environments. Additionally, owing to the properties of birefringent materials, based on the direction of polarization of the second polarizer (called the *analyzer*), the color detected by the camera will change - this requires a unique mapping of color (also called *hue*) to orientation of the analyzer to allow the data to be decoded accurately and to allow the receiver(s) to be localized (positioned) on a 2D plane. This mapping is created for the two materials in both dark and ambient environments to determine their similarities/differences, and deduce their suitability for a VLP system.

The paper is structured as follows. Section 2 introduces the concepts of *Light Modulation*, *Polarization* and *Birefringence*. Then, Section 3 identifies the components of a VLP system, and formulates the research questions this paper will answer. Section 4 explains the methodology used to derive answers to the questions presented. Section 5 details how the experiment was conducted and evaluates the results derived. Following this, Section 6 highlights the conclusions reached based on these results and Section 7 discusses some of the ethical considerations for the VLP system and this paper. Lastly, Section 8 briefly summarizes the paper, with some suggestions for further research. Appendix A provides further details on the experimental set up to allow reproducibility.

2 Background

To understand the use of static polarized color patterns, *Light Modulation*, *Polarization* and *Birefringence* are concepts that warrant a discussion. The following paragraphs describes these concepts with regards to the analysis proposed in this paper.

Light Modulation

Modulation is a technique used to change/process signals to communicate data. Visible Light can be modulated in two ways: Active and Passive.

Active Modulation requires the switching on/off of lights and/or power supply to generate the 1s and 0s to transmit data. There are various such schemes, some worthy of mentioning include Binary Frequency Shift Keying [8; 9], Pulse Position Modulation [13] and Manchester Encoding [6; 14]. This is possible for LEDs because of their ability to instantaneously switch on/off [8], making it feasible to rapidly communicate/transmit data. However, active modulation often requires high power consumption due to this rapid switching on/off of LEDs. Additionally, it can cause visible flickering which can cause human health problems [18] - this would not be ideal for places such as a supermarket or a retail store.

Passive Modulation aims to distort light, for example through the use of polarizers and birefringent materials (see the next two sub-sections), to create decodable color patterns which are not only invisible to the human eye, but consume next to no power. In effect, light is modulated by changing/twisting its direction and/or dispersing the light to form different colors to communicate the required data.

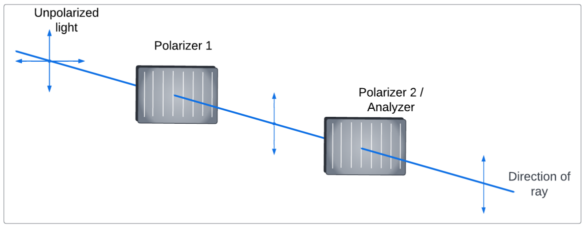

Figure 5: Polarization with analyzer placed parallel to first polarizer

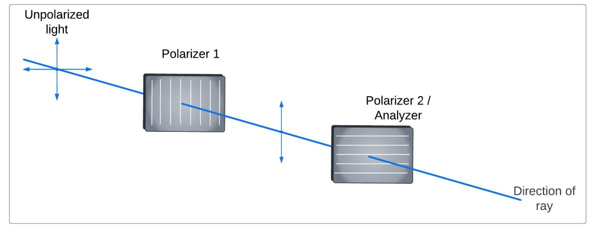

Figure 6: Polarization with analyzer placed orthogonal to first polarizer

Polarization

In general, light is *unpolarized*, it oscillates in all possible directions. A polarizer blocks all directions of oscillation except one, known as the axis (direction) of polarization. It should be noted that polarization is not visible to the naked eye. Figure 5 shows unpolarized light passing through two parallel polarizers, allowing only one direction of light to pass, in contrast to Figure 6 which shows unpolarized light passing through two orthogonal polarizers (effectively, blocking all light).

Polarized light can then be passed through either a birefringent material (see subsection below) or a dispersor to attain only certain directions/colors of light. This effectively allows a controlled modulation of light that does not involve any switching on/off of light.

Birefringence

Birefringence, also known as bi-refraction, is the refraction of incident light (i.e., the bending of light) through a material into two rays - called the ordinary ray (parallel polarization) and extraordinary ray (perpendicular polarization). This is depicted by Figure 7.

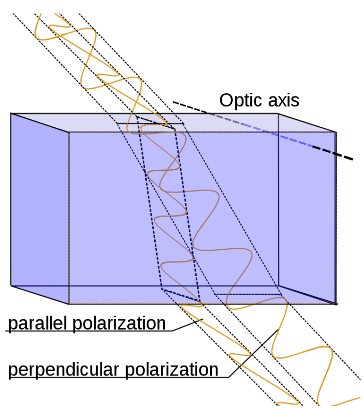

Figure 7: Bi-refraction of an incident light through a birefringent material into two polarized rays. [2]

Birefringence effects are not visible to human eye, but these can be visualized by placing this material between two polarizers. When the bi-refracted rays - of different wavelengths, and travelling at different speeds - are captured by a lens (either the camera or eyes), they form a distinct color.

(a) Analyzer placed at 90 degrees to first polarizer

(b) Analyzer placed at 110 degrees to first polarizer

Figure 8: Transparent adhesive tape placed between two polarizers displays birefringence effects.

Assuming the first polarizer remains static, this color is based on the direction of polarization of the second polarizer (*analyzer*). Figure 8 shows such an example of birefringent transparent adhesive tape, with the analyzer placed at 90 degrees and at 110 degrees to the first polarizer. The color pattern can be captured by a camera. This provides the ability to encode data into color patterns which can then be decoded by a camera, establishing a uni-directional communication channel.

3 Visible Light Indoor Positioning

Visible Light Communication has various applications, one of which is indoor positioning (see Figure 4). Visible Light Positioning systems are built from four components:

- Transmitter - modulates light signals either statically (through polarization and birefringence) or dynamically (on/off keying of lights). Ideally should be low-cost and relatively easy to maintain.
- Receiver - demodulates received light signals to extract data transmitted. Ideally should also be low-cost and light weight.
- (De)Modulation scheme - the way light will be (de)modulated in the system to (en/de)code data.
- Localization scheme - upon receiving data from transmitter(s), the system should be able to use it to localize/position the receiver(s) in the given room/environment.

This paper focuses on the use of Static Polarized Color Patterns. It has the following consequences for each of the components mentioned above:

- Transmitter - to modulate light, we only need to place a polarizer at the light source - which could be either artificial or natural - and create the required pattern with a birefringent material. This is cost-effective, with zero power consumption. This modulation is invisible to the human eye.
- Receiver - only a simple off-the-shelf camera and a polarizer (analyzer) is required to capture the color patterns. The polarizer adds virtually no weight to the receiver.
- (De)Modulation scheme - since we only need to communicate the identifiers for each light source, a static pattern that uniquely encodes a single identifier can be achieved by creating a grid pattern, similar to the one in [12], Figure 3.
- Localization scheme - this paper does not touch upon an in-depth localization scheme. The general idea for 2D Localization would be to read the identifier data based on the color pattern detected, and use the hue-orientation mapping (see section 4) to decide the orientation of the receiver and hence deriving an approximate position. This could further be extended in a similar way to RainbowLight [7] to perform 3D localization.

Polarized color patterns can either dynamically or statically modulate light. Dynamic modulation can be achieved through either rotating disks (called *shades*), as in [15; 17], or through the use of Liquid Crystals (LCs) [13; 18]. However, both these methods lead to some amount of power consumption (having to change the voltage of LCs) and/or maintenance costs (delicately formed shades may not work correctly if they are even slightly damaged). In contrast static modulation does not need any external source of energy and can be easily implemented in existing lighting infrastructure for a low cost.

Research Question

The birefringent material of choice in most such systems is transparent adhesive tape. However, there are a wide variety of other birefringent materials that are just as easily available, one of which is plastic/cling-wrap (made out of PVC). This paper dives into the two birefringent materials mentioned, transparent adhesive tape and cling-wrap, to analyze their usability for creating such polarized color patterns for indoor positioning. The following questions are answered, with regards to each of the materials:

1. What is the visibility range of the material?
2. Can the material's colors/hues be mapped at the different analyzer orientations to help with the localization process?
3. Is the material reliable in both dark and ambient light conditions? Why, or why not?

4 Methodology

To analyze and deduce the answers to the questions in Section 3, the experimental set up shown in Figure 9 was used. A series of experiments were conducted with this set up. For further details on the experiments themselves, see Section 5. The following subsections explain the methodology used for each of the questions.

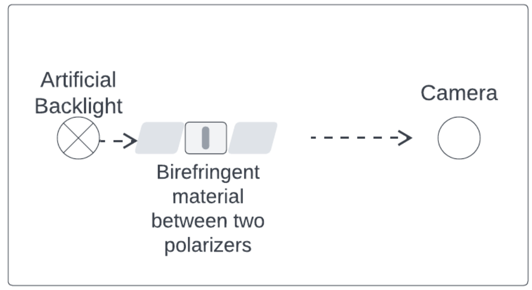

Figure 9: Experimental set up: An artificial light source with a glass panel in front of it. Two polarizers are placed on either side of the glass panel with a strip of the birefringent material on one side of the glass panel. The camera captures the color of this strip in different environments.

Visibility Range

Visibility range, in case of VLP systems, means that the camera should be able to detect the pattern and its color at varying proximity from the light anchor. It is the set of hue (color) values we can expect the camera to detect, regardless of the proximity of the camera to the light anchor. To determine the visibility range of a birefringent material, the camera in the given set-up was placed at increasing, linearly-spaced intervals from the glass panel, and the hue (color) and intensity detected at each point were recorded. This was done without changing the orientation of the analyzer. At each point, the color detected should be approximately the same - indicating that the camera is able to discern the color (and pattern) regardless of distance.

Hue-Orientation Mapping

The hue-orientation mapping of a birefringent material, in VLP systems, allows the localization scheme to determine the receiver's orientation, that is, given the color it detects in the pattern, it should be able to tell which way the receiver is facing (in a 2D plane). To determine this mapping, the camera in the given set-up was placed at a fixed distance from the glass panel. The analyzer's orientation was determined as the angle between its axis of polarization to the first polarizer's. The hue (color) was recorded at a fixed set of orientations. This mapping of hue to orientation would enable a camera to determine the orientation of the polarizer and hence allow it to localize/determine the position of the receiver.

Different Light Environments

Given that most indoor spaces have extensive lighting infrastructure, it would be impractical to expect a dark environment. This implies that the camera should be able to detect the colors of the material regardless of ambient light interference. To that end, the above experiments were conducted in both dark and ambient light environments. In the case of determining the visibility range, in both environments, the color detected should ideally be within a small range from each other. In the case of hue-orientation mapping, the mapping should closely follow each other in both environments, indicating its invariance to ambient light interference.

Hue Detection Algorithm

A color space represents an organization of colors in a structured way, using a set of parameters. Two of the most common such color spaces/models are RGB (mixtures of red, green, and blue) and HSV (hue, saturation, value). It should be noted that the HSV color model would be more suitable to represent/detect the color of mixtures of light compared to the RGB model [1]. RainbowLight [7] also notes that it would be impractical to map RGB vectors to orientations since it is not descriptive enough to represent the light spectrum, as compared to the HSV model.

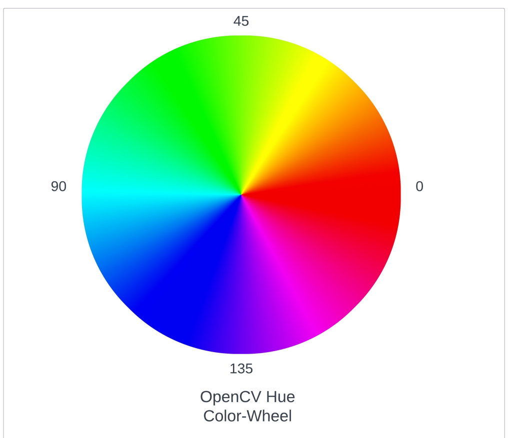

Figure 10: Hue Value Wheel (Python OpenCV version). *Source: Image by Pete Linforth from Pixabay*

To detect this hue value (which ranges from 0-180 in Python's OpenCV, see Figure 10), the images were first manually cropped so that the strip of cling-wrap/tape was centrally aligned, and covered approximately one-third of the area (see Figure 8). Then, the central pixel of the image was selected (which, in all cases, selected the center of the strip of tape/plastic). The image was converted to HSV (since they are usually stored as RGB) and the hue-values of the image were averaged over 9 pixels - the central one, and all its neighbours - to get an approximate hue value (Figure 11)

5 Experimental Set-Up and Evaluation

5.1 Overview

The experimental set up shown in Figure 9 was created in a lab (see Figure 12). A laptop screen was used as the source of artificial backlight (white). The glass panel was placed in

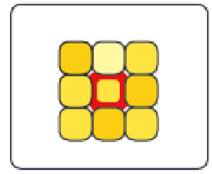

Figure 11: Central pixel (highlighted red) is detected. Then the hue value of this pixel and all its neighbours are averaged to reach an approximate hue value.

front of the screen, with two polarizers taped to either side of it. Between the polarizers, the birefringent material was placed. The camera used was a Samsung Galaxy A42 5G handheld mobile device with a Quad camera. It was placed on a tripod, orthogonal to the light source at all times. The pattern chosen for the experiments can be seen in Figure 13. Camera and laptop specifications, and dimensions of the glass panel, polarizers and birefringent materials used can be found in Appendix A.

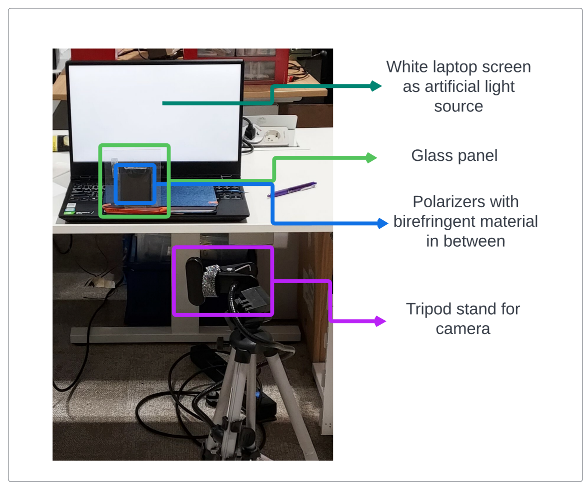

Figure 12: The experimental set-up in a lab. A laptop screen, acting as a backlight can be seen, with a glass panel in front of it. The glass panel has a polarizer on either end, with the birefringent material in between. The phone-camera is held on a tripod.

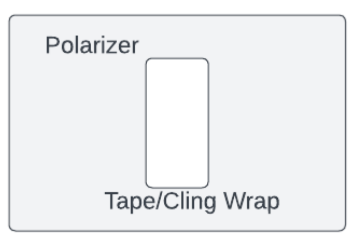

Figure 13: Pattern chosen for all experiments - a single rectangular strip of the material.

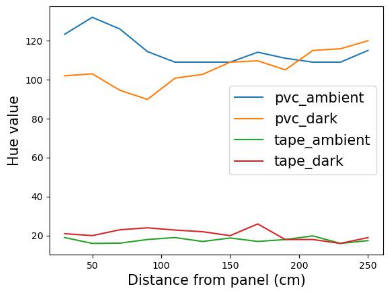

Figure 14: Hue vs Distance graph - PVC (cling-wrap) and Tape in both dark and ambient environments

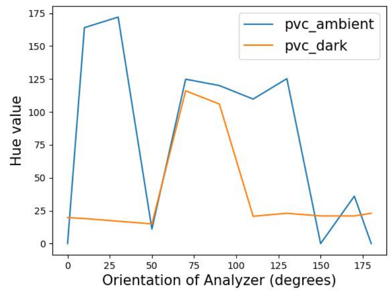

Figure 15: Hue vs Orientation graph - PVC (cling-wrap) in both dark and ambient environments

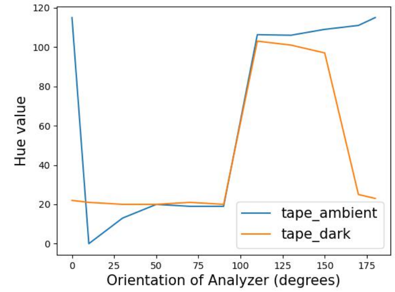

Figure 16: Hue vs Orientation graph - Tape in both dark and ambient environments

5.2 Results

Visibility Range

For both materials, the analyzer was placed at an orthogonal position to the first polarizer. Starting at 30 cm from the glass panel, the camera was moved backward at intervals of 20 cm, up to 250 cm. The hue value was then detected at each point through the algorithm mentioned in section 4. The results can be seen in Figure 14.

For transparent adhesive tape, the hue value detected is within the range of 18-21 in both dark and ambient environments, regardless of the distance. The variance is very low and the hue detection is reliable.

However, for PVC (cling-wrap), the hue value detected in a proximity of about 30-130 cm from the glass panel ranges between 90-130. This is about 10 times less reliable than adhesive tape. However, at distances further away ($>$ 130 cm), the hue value seems to converge in the range of 110-120 (regardless of the type of environment), indicating that it may still be used for indoor positioning systems assuming that the camera would not have to be in such close proximity to the light source.

Hue-Orientation Mapping

For both materials, the camera was placed at a distance of 30 cm from the glass panel. The analyzer was rotated clockwise, starting from 0 degrees, up to 180 degrees. The hue was detected, once again with the algorithm mentioned in Section 4. The results can be seen for PVC (cling-wrap) in Figure 15 and for adhesive tape in Figure 16.

In case of PVC, the color detected in the two different environments varies greatly with minimal overlap in the 50-75 degree range. In the dark environment, the colors detected form an almost symmetrical bell-curve around the 75-degree mark. This is not desirable because the hue-orientation mapping should be an approximately *injective* function - each hue value should be mapped to one orientation.

In comparison, for adhesive tape, the color detected in the two environments overlaps from about 25 degrees to 150 degrees with an error in hue value of up to +/- 5. Additionally, the colors detected are in an approximate step-pattern, instead of the bell-curve formed for PVC, making it easier to derive the exact orientation of the receiver based on color detected.

6 Discussion

The results provided in section 5 show that between transparent adhesive tape and PVC, adhesive tape is more reliable to create static polarized patterns and provides both distance-invariance and reliable hue-orientation mapping, that is, the camera is able to capture the color accurately over a wide range of orientations and distances. Additionally, transparent adhesive tape is also unaffected by ambient light interference.

While PVC provides some reliability for larger distances, its bell-curve shape of hue-orientation mapping would not make it suitable for indoor positioning, since it would not be possible to tell the receiver's orientation based on the hue detected - hindering the localization process. It can also be seen in Figure 15 that ambient light drastically changes the hue detected, distorting the bell-curve shape even further.

Taking all of the above into account, it is possible to derive that transparent adhesive tape is reliable to use for indoor positioning systems. If the tag to be placed at the transmitter is made using adhesive tape, the camera/receiver will be able to, more or less accurately, detect the right color regardless of how far it is from the light source. Additionally, if, for example, the camera detects two light anchors, it will be able to decide the orientation of the receiver based on the colors detected and hence accurately position the user in the indoor space (not unlike the way GPS positioning systems would localize the receiver).

7 Responsible Research

Technology works largely on electricity, and with its widespread use, power consumption rates are very high. For the indoor positioning system proposed here, this aspect had to also be taken into consideration.

While polarized color patterns do provide better accuracy [7; 12; 13; 15; 17; 18] compared to using the on-off keying of LED lights [6; 8; 9; 14] or the use of intrinsic frequency data [10; 11; 19; 20], another important reason to use them is because of their lower/zero carbon footprint.

Dynamic color patterns need only low power consumption (for example for LCs) since they do not suffer from the flickering problem. Static color patterns on the other hand need next to no power consumption at all, making them not only easy to implement and use, but also eco-friendly.

Additionally, it was important for this research to be reproducible. To that end, Appendix A provides all necessary details needed to repeat the same set of experiments conducted in this paper.

8 Conclusions and Future Work

Visible Light Indoor Positioning systems (VLP) are a promising technology of the future, with applications in various industries. To make them easy to implement and cost-effective, it is necessary to look into the four components - transmitters, receivers, modulation scheme, and localization scheme - to identify the most efficient version of each that work together. To that end, this paper analyzes the use of two birefringent materials - transparent adhesive tape and PVC - to create static polarized patterns for passive modulation of light.

The materials were tested for their visibility range, hue-orientation mapping, and ambient light interference. It was shown that, due to the bell-curve shape of the hue-orientation mapping found for PVC, it would be unsuitable to use for a VLP system, since it would not be able detect orientation accurately, making it incapable of localizing the receiver. Additionally, PVC suffers greatly from ambient light interference. In contrast, adhesive tape proved not only to have a very useful hue-orientation mapping owing to its step-pattern, but also proved to be reliable and accurate at detecting color at different distances and orientations in both dark and ambient light conditions.

Using static color patterns is not only easy to implement and cost effective, but is also eco-friendly and easy to maintain in the long run. However, this paper has not covered the use of different light sources (such as sunlight, warm/colored lights, etc.) and the effect of the angle of arrival of light on the color/hue detected. The receiver was always placed orthogonal to the light source. Additionally, only one kind of camera was used for the given set of experiments. However, the accuracy of the color detected could change based on the camera's specifications. All of the above points could be a potential starting point for further research.

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A Details of Experimental Set-up

Figure 17 shows the dimensions used for the polarizers, glass panel, and for the strips of Adhesive Tape and PVC (Cling-Wrap).

Dimensions	Width	Height
Polarizers	7.4 cm	5.7 cm
Glass panel	12.6 cm	12.6 cm
Tape/Cling Wrap	1.2 cm/2.4 cm	4.4 cm/4.5 cm

Figure 17: Dimensions of Polarizers, Glass Panel, and Adhesive Tape/PVC

A Samsung Galaxy A42 5G phone-camera was used throughout this experiment. Figure 18 details the specifications of the Quad-camera. The laptop used was a Lenovo Legion Y540-15IRH (type 81sx).

Camera Specs			
Quad	Resolution	Focal Length	Type
1	48 MP	f/1.8	wide
2	8 MP	f/2.2	ultrawide
3	5 MP	f/2.4	macro
4	5 MP	f/2.4	depth
Video Features	Resolution	Frames per second	
	4K	30	
	1080p	30	
	720p	480	

Figure 18: Camera specifications of Samsung Galaxy A42 5G's Quad camera

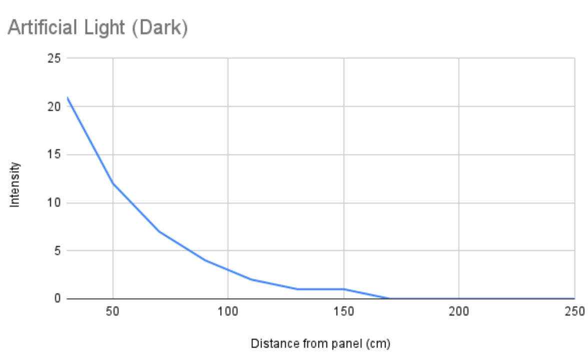

Figure 19: Light Intensity vs Distance in a dark environment

Graphs 19 and 20 show the light intensity variation (in LUX) at increasing distance from the glass panel (in cm) in the lab-environment in both dark and ambient conditions.

Figure 12 shows the experimental set up in the lab. The laptop screen was simply a blank white which worked as the

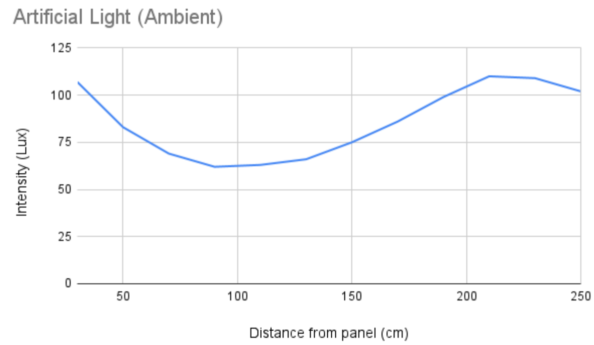

Figure 20: Light Intensity vs Distance in an ambient environment

artificial light source. The polarizers were taped to the glass panel. (Note: glass panels do not exhibit birefringence, and hence, would not interfere with the experiment).

It should be noted that, initially, the analyzer was to be placed on the camera. However, there was too much diffusion of light making the camera incapable of focusing and taking a picture of the pattern. Hence, the analyzer was also placed on the glass panel. Additionally, all readings are prone to some parallax errors, even though utmost care was taken to minimize these - for example, markers were placed on the floor to indicate distances, and were used consistently for all measurements.

The pattern chosen for the experiments was a simple rectangular strip, as seen in Figure 13. This was because the aim of the experiments was to deduce if the colors and the simple pattern are discernible by a camera, instead of focusing on the choice of pattern that would communicate the most data.

Lastly, it should be noted that for the hue detection algorithm mentioned in Section 4, the images taken were of aspect ratio 1:1 and were manually cropped so that the tape/cling-wrap covered approximately one-third of the image and was aligned approximately to the center of the image.