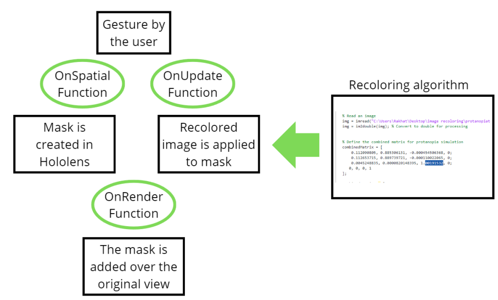
The implementation of the real-time correction of colors for a colorblind (daltonian) person using HoloLens(1st gen.)

Dias Akimbay, Bekmurat Amangeldiyev, Bauyrzhan Askarov,
Rakhat Ospanov and Zhanat Kappassov *Member, IEEE*

***Abstract*—With the rise in the progress of digital technologies, the number of everyday problems in the lives of colorblind people continues to increase. Therefore, the main objective of this research is to create a solution to these issues via the use of image processing methods and augmented reality implementation. Through the investigation of the list of existing solutions and academic articles' observations, we are aiming to create the most reliable tool for colorblind individuals. Specifically, in the scope of this paper, we are going to implement an Augmented Reality Solution that will support its users to better distinguish color combinations. Consequently, different recoloring algorithms along with segmentation methods are going to be utilized in Hololens generation glasses.**



***Index Terms*—Image recolorization, Augmented reality, Color vision deficiency, Finger interaction.**

I. Introduction

Colorblindness, a prevalent visual impairment, significantly impacts an individual's ability to perceive and distinguish colors accurately. A promising avenue is presented for assisting colorblind individuals with Augmented Reality (AR), particularly using HoloLens technology. By consistently taking into account the entire visible area, HoloLens will recognize objects and their colors in real-time. Subsequently, an adaptive color recoloring algorithm is applied to modify the RGB and HSV values of detected objects and colors, ensuring convenience and enhanced perception for individuals with color vision deficiencies (CDV) [1]. This research mainly focuses on leveraging AR to improve color perception and facilitate object recognition for people with colorblindness, in particular protanopia, deuteranopia, and tritanopia. Ultimately, it will enhance their overall interaction with the environment.

According to the following research work [1], there exist a few color vision deficiencies among the human population. These CVDs depend on the absence or lack of different photoreceptor cells, the cone cells. By their spectral sensitivities, cones are divided into three groups, which can absorb different wavelengths: long- (L), middle-(M), and short-(S).

Overall, there are three types of CVDs: monochromacy, dichromacy, and trichromacy. In this research work, we will focus on dichromacy and trichromacy. Monochromacy is the severest case among all types of colorblindness, where the individual can perceive only the brightness without coloring. The information on types of color blindness can be seen in Fig 1.

II. Related Works

The following analyzed research papers will be sorted in order of publication and industry chronology(2006-2020).

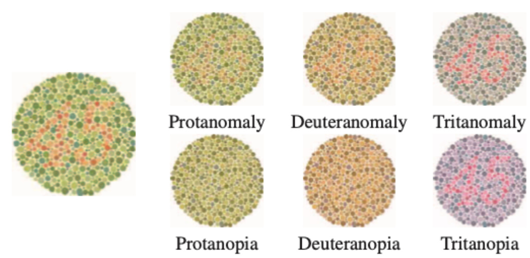


Fig. 1: Types of color blindness.

In Iaccarino et al. work, the authors were one of the first who used image processing algorithms in order to modify the images for colorblind people [1]. More specifically, they increased the brightness of each image, which led to successful results with patients.

After that, the number of papers in this field drastically increased. Some researchers just started the implementation of this technology in real life, such as Ohkubo T. and Kobayashi K., who created algorithms for the recolorization of traffic light colors with the use of old AI versions for specific colorblindness [2]. For example, if the person is unable to see the red color, it is changed to a blue color. Analogically, the same method is applied to other colorblindness [2].

Later, other scientists also started to research this area more deeply to increase the effectiveness of such algorithms. The group of researchers of Huang's group introduced a brand new approach in this field, rather than increasing the brightness of the original color they re-mapped the hue component of the HSV color space based on the local characteristics of the original color image [3]. In their next paper, the researchers improved their methodics with the use of probability distribution techniques [4].

Similar to Huang et al., other studies have been conducted by a large number of groups all over the world. In their paper, Kuhn et al. proposed a similar approach, however, their results were more precise since they tried to save the original colors as much as possible [5].

Later, with the achievement of much better algorithm results, the number of industry applications has significantly increased. This way the state-of-the-art for that time AR application named ”Chroma” was invented [6]. According to the research of Tanuwidjaja et al., the main purpose of this device was to create the most convenient technology based on different approaches to image recoloring and segmentation methods. In their survey, all participants considerably improved their results after repeating the same colorblindness test [6].

Furthermore, some interesting industry approaches have occurred, such as the work of Manaf et al, who combined Machine Learning and Image Processing algorithms for colorblindness [7]. Specifically, they designed AR glasses that were able to change a specific color pointed by a user's finger [7].

Consequently, some papers, that compare different versions of AR approaches for people with colorblindness, have appeared, such as the work by Salih et al. [8]. The discussion in this field is still ongoing, among the most recent research the work of Li et al. should be mentioned [9]. In their research, they not only analyzed the works done by previous teams but also introduced the methods of adversarial networks which are applied to inversely transform the corrected colorblind image into a color image in agreement with the input [9].

Therefore, as the discussion on this topic still continues, we are going not to only analyze, compare, and utilize the recently achieved approaches, but also contribute our own ideas to this field. Precisely, first, we are going to implement some segmentation approaches as discussed in the paper of the use of image analysis and neural networks [10]. Secondly, with the use of M. Riberio and A.J. Gomes paper, we want to achieve and compare some new approaches for image recolorization for colorblindness [11]. Thirdly, using the work of utizilation of hololens for driving condition awareness, we will try to implement this technology similarly on Microsoft HoloLens 1.0 [12]. In terms of AR Implementation, this source is sufficiently helpful with this concern. According to the author, the implementation of our solution on the HoloLens system requires the use of Visual Studio code along with C, and Unity3d programs usage [12]. Nevertheless, the first examinations are going to be achieved via Matlab.

III. Methodology

A. Hololens Setup

Throughout this study, every step is in line with the advancement of image recolorization using AR Hololens 1.0. This part is intended to be integrated into the device to show how the re-coloring methods can be used to meet the needs of individuals who are colorblind. The Universal Windows Platform, or UWP development platform, which enables the use of augmented reality in Windows devices, is the main connection point for Hololens configuration. Since it supports all of the components required for connectivity, installing the relevant Visual Studio IDE version is necessary in this instance to configure the Hololens and the device (PC). Selecting the appropriate version relies on the application that must be used; for the first generation of Hololens, there are differences between 2017 and 2019. For the IDE, it is advised to use the 2017 version, though, as some versions might have connection issues. This is why it's important to carefully follow the Microsoft instructions, as the compatible device settings vary depending on the Hololens generation. In terms of deployment, there are essentially two ways to implement the deployment procedure: either via USB connections to enable data transmission, or via the internet (Wifi). For convenience, we decided to use internet connectivity for AR implementation. It is done through the application of the IP address of the wifi to connect two devices and transfer the required data between of them. Since installation requires additional tools to be involved for different engines, it is hard to know beforehand what toolsets to be installed. In the implementation, most papers considered using the Unity engine for research purposes in image processing, however, applied only object detection. It is relatively hard to find in our case of recoloring methods whether or not the algorithm will work for the entire environment of the virtual world of Hololens or simply in objects created from Unity itself. The actual method we used is described in the next section.

B. HololensforCV

It was discovered that there is, however a tool for direct image processing applications to the Hololens, without any use of third-party platforms such as Unity. In the context of this research, the HololensforCV library provided by the Microsoft Team was utilized. The basic purpose of this tool is to provide the abilities of Hololens Research mode, via the demonstration of the way to access it and use it.

However, HololensforCV does not present full freedom of action. The majority of its business mainly consists of the provision of access to some inner functions of Hololens device, such as the functions that are run after some gesture was recognized or the every second updated function. In terms of the ”access”, it should be mentioned that the ”access” is considered not in the way to call them, delete, or change their initial structure. Nevertheless, a user can add some additional scripts to these functions.

Therefore, for the utility of this research, a short manual regarding the HololensforCV functions is going to be provided and described.

(a) ”OnSpatialInput” function of App::main. As the name says, this function is mainly used to work with some spatial parameters of Hololens. More specifically, it provides a developer with data regarding the position of Hololens, the user, and the angle of interaction. Furthermore, this function is only called when a gesture of ”Two fingers button” is recognized by the Hololens.

(b) ”OnUpdate” function of App::main. This function is run every constant time interval, which also can be defined in this function. The data that is accessed throughout this function is the frames illustrated by the Hololens. Thus, the image processing, computer vision, and algorithm definition parts should be placed here.

(c) "OnRender" function of App::main. This function is mainly concerned with the update of frames. It can be stated, that through this function all the updated frames provided by the "Onupdate" function are represented in the window illustrated by the Hololens device.
As it can be observed, through the application of the HololensforCV library and the Hololens Research mode the purpose of this project can succeed. Fig. 3 demonstrates the scheme of the HololensForCV script, which we utilized for the project pipeline.

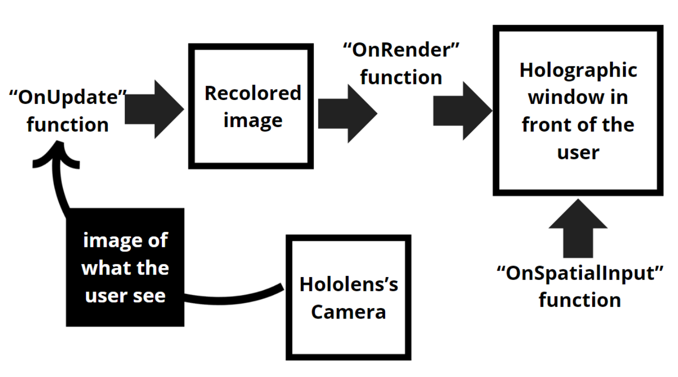


Fig. 2: HololensForCV scheme

According to this figure, it can be mentioned, that firstly, the "OnSpatialInput" creates a window in front of the user. Then the "OnUpdate" function changes the original scene of what the user sees via the use of image processing algorithms and the images obtained from the HoloLens camera. Then, as the Recolored image is obtained it is transmitted to the create window in front of the user via the use of the "OnRender" function.

C. Algorithms of color recolorization

Our image processing algorithms were mainly based on the following work [13]. We used the LMS algorithm based on this paper since it is suited to all types of dichromacy(Protanopia, Deuteranopia, Tritanopia) colorblindness and is the most convenient to use with Hololens glasses.

It should be noted, that the LMS algorithm is based on the use of LMS color space, where each letter defines the specific range of waves a human eye can perceive, L - long, M - medium, and S - short. The transformation of RGB color space to LMS color space is processed through matrix multiplication.
Throughout the algorithm, the pipeline can be divided into two sections: colorblindness simulation and colorblindness correction. In the first part, the simulation of the specific colorblindness type is processed through matrix algorithms. Consequently, these simulated images are then used to correct the colors of the image for the Colorblind user.

Description of the LMS Daltonization algorithm [14]
Input: RGB input image
Output: RGB color corrected image

Step 1. The first step is to convert all RGB pixels of the image to LMS color space. It is achieved by using the matrix(1) provided below:

$$\begin{bmatrix} L \\ M \\ S \end{bmatrix} = \begin{bmatrix} 17.8824 & 43.5161 & 4.11935 \\ 3.45565 & 27.1554 & 3.86714 \\ 0.0299566 & 0.184309 & 1.46709 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix} \quad (1)$$

Step 2. The next step is to apply specific matrices for each type of Dichromacy colorblindness: Protanopia(2), Deuteranopia(3), and Tritanopia(4). These matrices will transform the LMS images into the spectrum of certain diseases:

$$\begin{bmatrix} L_P \\ M_P \\ S_P \end{bmatrix} = \begin{bmatrix} 0 & 2.02344 & -2.52581 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} L \\ M \\ S \end{bmatrix} \quad (2)$$

$$\begin{bmatrix} L_D \\ M_D \\ S_D \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0.49421 & 0 & 1.24827 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} L \\ M \\ S \end{bmatrix} \quad (3)$$

$$\begin{bmatrix} L_T \\ M_T \\ S_T \end{bmatrix} = \begin{bmatrix} 1.0 & 0.0 & 0.0 \\ 0.0 & 1.0 & 0.0 \\ -0.395913 & 0.801109 & 0.0 \end{bmatrix} \begin{bmatrix} L \\ M \\ S \end{bmatrix} \quad (4)$$

Step 3. After acquiring images for each type of disease in LMS color space, we return the images back to RGB space using the matrix (5):

$$\begin{bmatrix} R_i \\ G_i \\ B_i \end{bmatrix} = \begin{bmatrix} 0.0809444479 & -0.130504409 & 0.116721066 \\ 0.113614708 & -0.0102485335 & 0.0540193266 \\ -0.000365296938 & -0.00412161469 & 0.693511405 \end{bmatrix} \begin{bmatrix} L_i \\ M_i \\ S_i \end{bmatrix} \quad (5)$$

Step 4. At that point, we have 2 images: the first is the original image, and the second is a simulated image for each type of color deficiency. Now we have to subtract each RGB pixel of the acquired image from the original to find the difference using (6),(7),(8). **Note:** The simulation images are important, and, even if they are not displayed, they should be calculated for future steps:

$$D_{R(i)} = R - R_i \quad (6)$$

$$D_{G(i)} = G - G_i \quad (7)$$

$$D_{B(i)} = B - B_i \quad (8)$$

Step 5. After all matrix multiplications and subtraction till step 4, some small errors might occur. Therefore, to be able to see the new images we need to shift colors to visible spectrum. It is completed via multiplying by error matrices for Protanopia(9), Deuteranopia(10), and Tritanopia(11):

$$\begin{bmatrix} R_{map(P)} \\ G_{map(P)} \\ B_{map(P)} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 \\ 0.7 & 1 & 0 \\ 0.7 & 0 & 1 \end{bmatrix} \begin{bmatrix} D_{R(P)} \\ D_{R(P)} \\ D_{R(P)} \end{bmatrix} \tag{9}$$

$$\begin{bmatrix} R_{map(D)} \\ G_{map(D)} \\ B_{map(D)} \end{bmatrix} = \begin{bmatrix} 1 & 0.7 & 0 \\ 0 & 0 & 0 \\ 0 & 0.7 & 1 \end{bmatrix} \begin{bmatrix} D_{R(D)} \\ D_{R(D)} \\ D_{R(D)} \end{bmatrix} \tag{10}$$

$$\begin{bmatrix} R_{map(T)} \\ G_{map(T)} \\ B_{map(T)} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0.7 \\ 0 & 1 & 0.7 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} D_{R(T)} \\ D_{R(T)} \\ D_{R(T)} \end{bmatrix} \tag{11}$$

Step 6. In step 6, to find the final simulated image as seen by people of one of the aforementioned diseases, we have to add each RGB channel of shifted colors to the RGB channels of the original image via equation (12), (13), (14):

$$R_{F(i)} = R + R_{map(i)} \tag{12}$$

$$G_{F(i)} = G + G_{map(i)} \tag{13}$$

$$B_{F(i)} = B + B_{map(i)} \tag{14}$$

In the following Figure 3, the simulation and corrected images using the aforementioned LMS Daltonization algorithm can be seen.

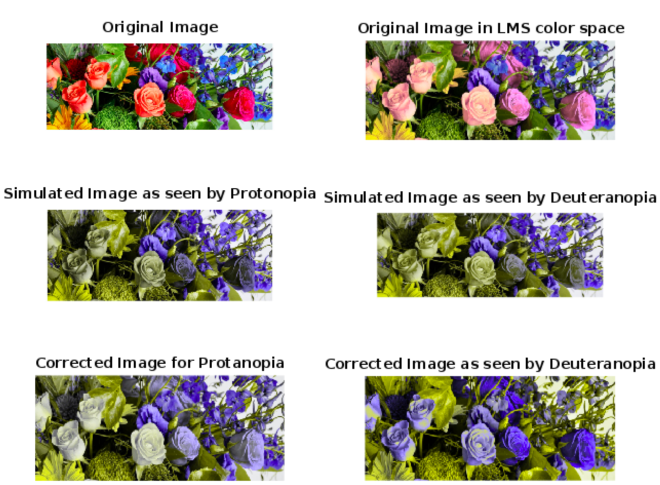


Fig. 3: Simulation and corrected images for Protanopia and Deuteranopia types of colorblindness in Matlab.

D. Algorithm for HololensforCV

Some notions regarding the algorithm implementation in Hololens devices must be included. First, the colorspace used in this device is BGRA (not common RGB), where B - blue channel, G - green channel, R - red channel, and A - alpha channel.

Therefore, in addition to the described algorithm above, we should add the colorspace transformation from BGRA to RGB in the beginning, and RGB to BGRA in the end.

Furthermore, as the spatial data is only accessed through the "OnSpatialInput" function, we cannot process obtain it every second. Therefore, the position of the frames should be constant all the time, until a user does not make a "Gesture".

IV. Experiments and Results

It should be noted that the two primary goals of our experiment are to represent the color vision of color-deficient patients using the Augmented Reality Hololens 1.0 device and to develop a color correction tool that will allow colorblind people to better distinguish their "difficult" colors.
As a result, our team conducted two types of experiments as part of our project, the first of which was Hololens Recoloring Simulation, which was based on the research of generating the view of people with some degree of color deficiency for normal people using Augmented Reality and the LMS recoloring algorithm. The second part of our experiments focused on color correction for people who are colorblind.
Furthermore, in the realities of our experiments, we considered three participants (colorblind people) with each having a high degree of red-green color deficiency. Thus, our experiments were based on protanopia simulation and correction.

A. Hololens Recoloring Simulation of Protanopia

The methodology section of our experiment details the LMS recoloring algorithm which aims to replicate the visual perception of an individual with colorblindness. It involves the manipulation of the original image's matrix, which is typical for normal vision. In this matrix, each pixel comprises varying degrees of the primary colors red, green, and blue. To achieve the recoloring effect, the original matrix must be multiplied by three distinct matrices. The first of these matrices is responsible for converting RGB values to LMS values. The second matrix varies based on the type of colorblindness: protanopia, deuteranopia, or tritanopia. The final matrix converts the LMS values back to RGB values. Therefore, it is clear that for the representation of the protanopia view, we are required to multiply the original image from the Hololens camera by these three matrices. However, for the better computational power economy of the Hololens first-generation device, we decided to reduce the number of matrix multiplications from three to one by preliminary multiplying three constant matrices.
As a result, our protanopia simulation algorithm can be described in only one equation:

SimulatedProtanopia =

$$\begin{bmatrix} 0.112090805 & 0.885306131 & -0.000454506368 \\ 0.112653715 & 0.889739721 & -0.000110022065 \\ -0.0045248835 & 0.0000820148395 & 1.00191532 \end{bmatrix} \quad (15)$$

$$*OriginalRGBMatrix$$

Therefore, the overall implementation pipeline of the Hololens Protanopia Simulation is described in Fig. 4.

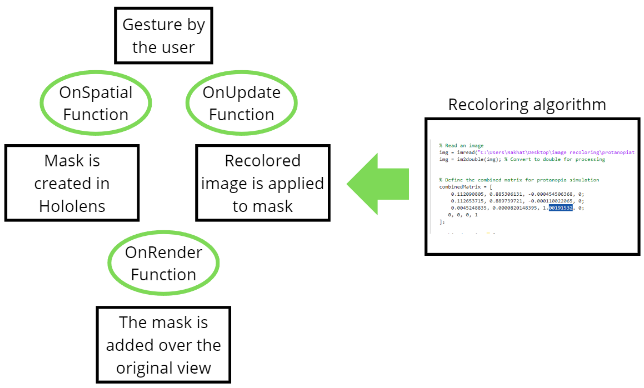


Fig. 4: Hololens Protanopia Simulation pipeline

According to this Protanopia Simulation implementation, we obtained the following results:
Figure 5 presents the rgb gradients seen using Hololens first generation and our protanopia simulation algorithm.

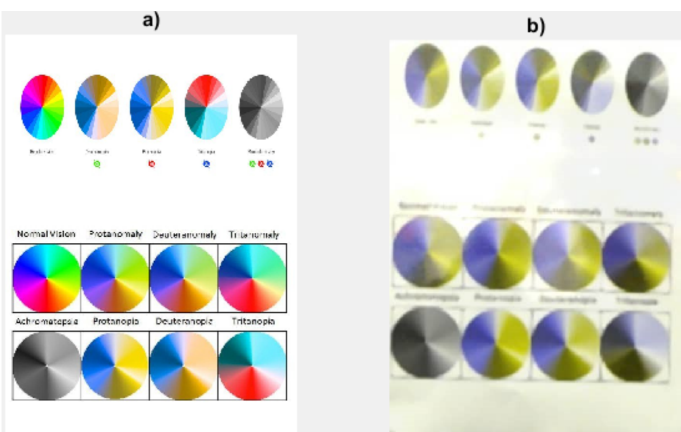


Fig. 5: Simulation of Protanopia from Hololens camera. a) Original Photo, b) The image seen in Hololens

Therefore, it is clear that our Hololens Protanopia Simulation solution is able to transform the view of a normal user regarding the Protanopia view. As is seen in Fig. 5 all the red and green colors became much less distinguishable. Nevertheless, the question "To what extent are the results accurate?" still remains.

To address this issue, our team has surveyed three red-green color deficient patients and our team members.
The survey consisted of 15 Ishihara test templates. Firstly, each member of our team was asked to find the number in each of the Ishihara test templates without Hololens. Secondly, three Protanopia colorblind participants were asked to give their results on the same question. Finally, members of our research team tried to find the numbers of Ishihara templates using Hololens Protanopia Simulation.
All the results were put into the table 1.

Members took test	Participants took test	Members(AR simulation test)
15	0	0
15	0	0
15	0	0

TABLE I: Results of conducted survey.

According to Table 1, it becomes clear, that our Protanopia Simulation using Hololens solution is to a very high degree accurate, as the results of the Ishihara test between the members of our team with Normal vision using our Hololens solution, and our colorblind participants are the same. In both of the cases our participants and members could not distinguish the numbers illustrated in Ishihara test templates, while our members without Hololens had no problems in these cases.

B. Hololens Protanopia Correction

In the second part of our experiments, we evaluated the accuracy of our Hololens Protanopia Correction Solution.

To find the answer, our team first conducted a "small" experiment, where we first found some objects with mostly red and green colors Fig. 6 a). Next, we simulated the view of a protanopia person through the Hololens implementation and verified that this kind of colorblind person is not able to distinguish two objects with red and green colors, in our case, it was a red cap and a sweater Fig. 6 b). Therefore, we also implemented the simulation of protanopia disease with the image correction and found that in this case, a protanopia person can distinguish these two specific items. Now, the cap has become blue, while the sweater remains green Fig. 6 c).

For the result, it was clear that our correction solution through Hololens recoloring worked fine, as the red color became blue, which is distinguishable for protanopia colorblind people.

Therefore, to prove our observations, our team managed another survey with three red-green deficient participants.
This time, we asked our participants to name the numbers they see in 15 Ishihara test templates with and without our Hololens Protanopia Correction tool. After the survey, we collected all the results in the table 2.

	Without Hololens Correction	With Hololens Correction
Colorblind Participant 1	0	11
Colorblind Participant 1	0	13
Colorblind Participant 1	0	10

TABLE II: Color Correction experiment

According to table 2, it becomes clear that in addition to our previous observations, our color correction solution implemented for the Hololens 1 generation device gives some considerable results. In all three cases, with different red-green

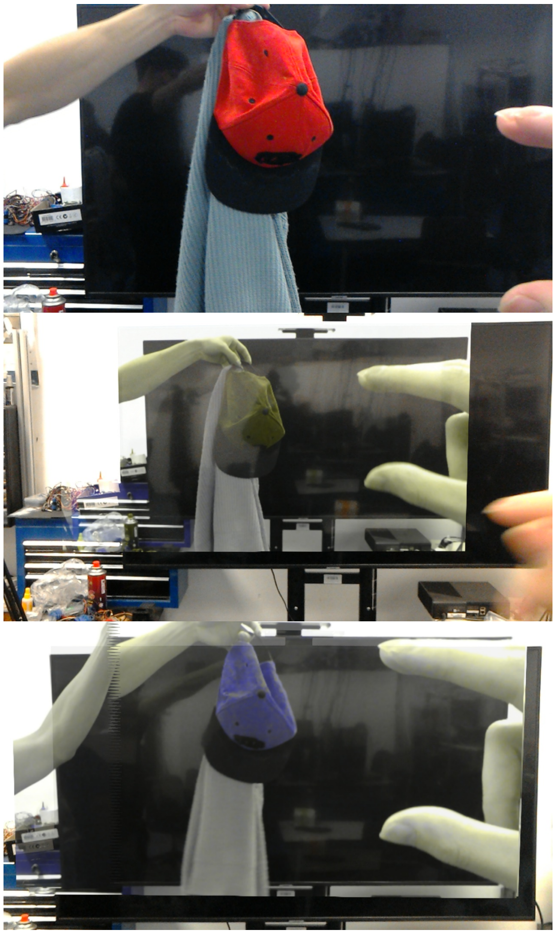


Fig. 6: Demo implementation of the LMS-based recoloring algorithm for Protanopia. a)Original image, b) Protanopia Simulation of the original image, c) Corrected image in Protanopia simulation

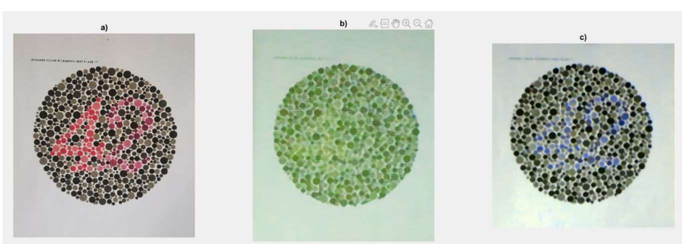


Fig. 7: Hololens color Correction of Ishihara test. From top to bottom: a) Original image, b) Protanopia Simulation of the original image, c) Corrected image in Protanopia simulation

color deficient participants their distinguishable abilities have significantly increased from the mean result of 0 to the mean result of 11.5.
The demonstration of our color correction Hololens solution from their view perspective can be seen in Fig.7, where b) demonstrates their representation of the Ishihara test, and c) represents their view with the use of our correction. It is visible, that the red color of the number became blue, while the red-black colors of the background became black-gray.

V. Discussion and Conclusion

Overall, our project has succeeded. Through the use of HololensForCV and Hololens' research mode presented by Microsoft Team we could implement different image recoloring methods to simulate the view of a colorblind people and create a correction tool for these color deficient patients.

Through several experiments conduction we obtained a quantitative proof of our approaches, where we observed that the results on colorblind simulation and correction parts are very high.

1) Image recolorization: Regarding the image processing part, it should be stated that in the scope of this research, we investigated the LMS recolorization method, which is widely popular among different sources.

As this method directly works with the representation of colors in terms of humans' eyes, it could provide us with good result and accurate representations.

2) Hololens implementation: This part required the majority of our time, as different approaches have been considered. Nevertheless, eventually, it can be stated that we succeeded in the implementation.

Through the use of the HololensForCV library, we could hardcode our implementation directly to the Hololens device without the use of any third-party applications.

Regarding the restrictions of this approach, we could not obtain a real-time permanent mask, as even if it translates the real-time data, the position of the mask is restricted to 3D coordinates (2 meters in front of the user after the "Gesture" was recognized), and is not updated as the user moves throughout the 3D coordinate system. Therefore, currently, to have the desired effect, the user should be stable in regards to the Real World Space system.

3) Segmentation: During the research our team has also succeeded in segmentation method. In this case, we considered segmenting different items from each other, through the sharp analysis and Hololens implementation.

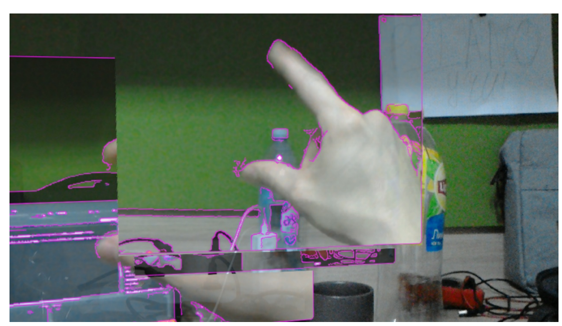


Fig. 8: Segmentation method in Hololens device

As it is seen in Fig. 8, it is also possible to divide different items through segmentation. Thus, a colorblind person can distinguish different items from his perspective.

A. Future work

As the experiment is mostly succeeded, there is still some job to be done.

1) Hololens implementation: In terms of Hololens implementation, it is required to create a stable mask not in terms of 3D Real World coordinates, as it is currently stated, but in terms of the user monitor. So once the mask is created in front of the user, the position of the mask(frames) should be updated based on the updates in the position of the user. Thus, the mask should be always in front of the user.

2) Image processing: Also, to broaden the number of methods that can be utilized by AR glasses, we intend to further work on our skillet-based recoloring algorithm for dichromats described in the work of Ribeiro M. G. and Gomes A. J. [14]. Furthermore, as the rest of the work is approximately done, our team can direct the majority of the power for the research of some other recoloring algorithms. Therefore, we also consider the various increases in the number of analyzed methods through AR glasses.

3) Survey and Segmentation: During our progress, our team has also attempted to get a contact with the local Center of Color deficiencies. Nevertheless, it is probable that the Center is currently inactive.

Therefore, we also considering contacting some other non-local research centers and continuing our work with their support. Specifically, we are going to conduct some surveys among colorblinders and get some expertise about our solution from the experts.
To be more specific, we are interested in the comparison between the segmentation-based approach and the recoloring-based approach. We are going to conduct a larger survey, where participants will be asked which approach is more convenient, comfortable, and accurate. A small variant of this large survey is presented in Fig. 9

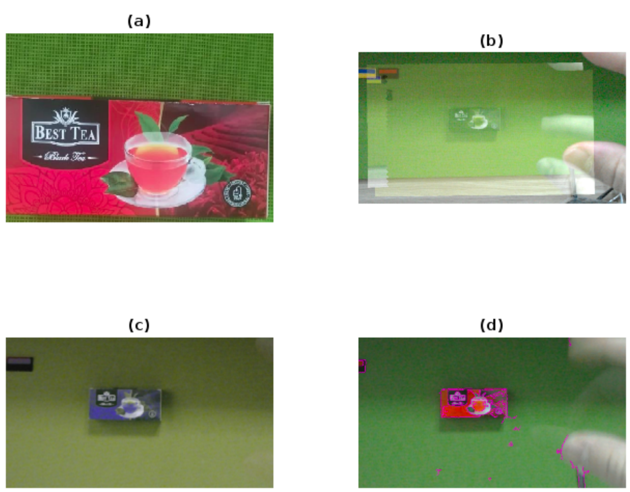


Fig. 9: Future survey. a) Original image; b) Protanopia view; c) Corrected image from protanopia view; d)image with segmentation mask.

REFERENCES

[1] G. Iaccarino, D. Malandrino, M. Percio, and V. Scarano, "Efficient edge-services for colorblind users," 05 2006, pp. 919–920.

[2] T. Ohkubo and K. Kobayashi, "A color compensation vision system for color-blind people," in *2008 SICE Annual Conference*, 2008, pp. 1286–1289.

[3] J.-B. Huang, S.-Y. Wu, and C.-S. Chen, "Enhancing Color Representation for the Color Vision Impaired," in *Workshop on Computer Vision Applications for the Visually Impaired*. Marseille, France: James Coughlan and Roberto Manduchi, Oct. 2008. [Online]. Available: https://inria.hal.science/inria-00321936

[4] J.-B. Huang, C.-S. Chen, T.-C. Jen, and S.-J. Wang, "Image recolorization for the colorblind," in *2009 IEEE International Conference on Acoustics, Speech and Signal Processing*, 2009, pp. 1161–1164.

[5] G. R. Kuhn, M. M. Oliveira, and L. A. F. Fernandes, "An efficient naturalness-preserving image-recoloring method for dichromats," *IEEE Transactions on Visualization and Computer Graphics*, vol. 14, no. 6, pp. 1747–1754, 2008.

[6] E. Tanuwidjaja, D. Huynh, K. Koa, C. Nguyen, C. Shao, P. Torbett, C. Emmenegger, and N. Weibel, "Chroma: A Wearable Augmented-reality Solution for Color Blindness," in *Proceedings of the 2014 ACM International Joint Conference on Pervasive and Ubiquitous Computing*, ser. UbiComp '14. New York, NY, USA: ACM, 2014, pp. 799–810. [Online]. Available: http://doi.acm.org/10.1145/2632048.2632091

[7] A. S. Manaf and R. F. Sari, "Color recognition system with augmented reality concept and finger interaction: Case study for color blind aid system," in *2011 Ninth International Conference on ICT and Knowledge Engineering*, 2012, pp. 118–123.

[8] A. E. Salih, M. Elsherif, M. Ali, N. Vahdati, A. K. Yetisen, and H. Butt, "Ophthalmic wearable devices for color blindness management," *Advanced Materials Technologies*, vol. 5, no. 8, p. 1901134, 2020. [Online]. Available: https://onlinelibrary.wiley.com/doi/abs/10.1002/admt.201901134

[9] J. Li, X. Feng, and H. Fan, "Saliency-based image correction for colorblind patients," *Computational Visual Media*, vol. 6, pp. 169–189, 06 2020.

[10] E. Hamzeloo, M. Massinaei, and N. Mehrshad, "Estimation of particle size distribution on an industrial conveyor belt using image analysis and neural networks," *Powder Technology*, vol. 261, pp. 185–190, 2014. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0032591014003465

[11] M. Ribeiro and A. J. P. Gomes, "Recoloring algorithms for colorblind people: A survey," *ACM Comput. Surv.*, vol. 52, no. 4, aug 2019. [Online]. Available: https://doi.org/10.1145/3329118

[12] R. Anderson, J. Toledo, and H. ElAarag, "Feasibility study on the utilization of microsoft hololens to increase driving conditions awareness," in *2019 SoutheastCon*, 2019, pp. 1–8.

[13] L. A. Elrefaei, "Smartphone based image color correction for color blindness," *International Journal of Interactive Mobile Technologies (iJIM)*, vol. 12, no. 3, p. pp. 104–119, Jul. 2018. [Online]. Available: https://online-journals.org/index.php/i-jim/article/view/8160

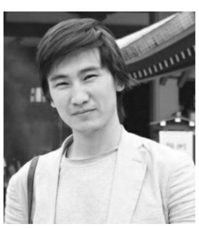
[14] M. G. Ribeiro and A. J. P. Gomes, "A skillet-based recoloring algorithm for dichromats," in *2013 IEEE 15th International Conference on e-Health Networking, Applications and Services (Healthcom 2013)*, 2013, pp. 702–706.

Dias Akimbay Nazarbayev University Robotics Engineering 3rd Year Student.

Bekmurat Amangeldiyev Nazarbayev University Robotics Engineering 3rd Year Student.

Bauyrzhan Askarov Nazarbayev University Robotics Engineering 3rd Year Student.

Rakhat Ospanov Nazarbayev University Robotics Engineering 3rd Year Student.



Zhanat Kappassov (M'16), received the Specialist degree in radio engineering from the Tomsk State of Control Systems and Radioelectronics (TUSUR), Tomsk, Russia. Afterward, he worked in the Industrial Technology Research Institute (ITRI), in Taiwan. He received his Ph.D. in robotics from the Institute of Intelligent Systems and Robotics (ISIR), Sorbonne Université (formerly Université Pierre et Marie Curie), Paris, France, in 2017. He is currently an assistant professor of robotics at Nazarbayev University, Nur-Sultan, Kazakhstan. His current research interests focus on tactile sensing for robot physical interaction and dexterous manipulation. He serves regularly as a reviewer for the IEEE Transactions on Robotics and IEEE conferences. His PhD thesis was nominated as the Best PhD Thesis 2017 by the GDR Robotique association in France.