Analytical Modeling and Verification of a Design for an Optical Assistive System

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Abstract

The people with total upper limb disability can access computer with their toes, artificial limbs, foot-operated mouse, or voice recognition that are either inconvenient or expensive. The study addresses the need for a low cost accessibility tool and one solution to it for the people with the disability. As a new solution to the challenge, a novel and low cost optical system was designed and developed which can have potential use in relatively convenient access to computer keyboard for people with the disability. The prime purpose of this article is to present a computational model, which has been developed for the system, and validation through experimental results. The theoretical data were found to match well with experimental ones that indicate the effectiveness of the design. The test results from the optical system reveal that foot-operated keyboard with high contrast key colors can be displayed at tabletop level for the targeted users, offering a potential option for the people with the disability to access a computer.

Keywords: Analytical Modeling, Assistive Technology, Computer Access, Optical System, Upper Limb Disability.

1. INTRODUCTION

Limb loss due to trauma or disease is, a global issue, causing disability and loss of personal freedom and job opportunity. Computer usage by the people with a disability is 25-50% lower compared to people without one (Koester et al., 2016). The mainstream information and communication devices and systems may be incompatible with assistive devices and assistive technologies; the upper extremity amputee may experience difficulty in using devices that require fine tune (WHO, 2011). However, productive access to computers is critical to improve the quality of life of the people with a disability (Anson, 1997; Chen, 2006). Voice recognition can be an option for the access to computer (Noyes & Frankish, 1992; Semary, et al., 2024) in this case;

however, it can be inconvenient in some situations. A foot-operated mouse (Betke, et al., 2002) can also provide access to computers to some extent which is comparable to the proposed system. However, the cost of the solution is prohibitively high (Boomer, 2025), which has typing option. Additionally, this type of device provides limited access and speed of using it (Garcia & Vu, 2011).In contrast, there are less expensive foot-operated secondary devices (mouse) available; however, they can offer limited access to computer such as PageUp and PageDown option; no typing function is available.

One software has been reported for web accessibility framework which offers the ease of the web accessing for the Arab disabled users (El-Soud & Shohieb,2010); it considers people with deafness and blindness. Literature exists on technology of brain computer interface (BCI) that can assist people with disability for both upper and lower limb disability (Chaudhari & Galiyawala, 2017). There has been research on eye controlled robotic arm for meal support system (Arai & Yajima, 2011). On the other hand, the current study focused on the people with upper limb disability who do not have the restrictions that the mentioned group of people do.

Disabled people in an economically challenged condition in underdeveloped or developing countries cannot easily afford artificial limbs (Cummings, 1996). People with an upper limb disability often find it inconvenient to use a prosthetic due to its size and weight (Chen, at al., 2006; Kawasaki, et al.,2007). To develop a prosthetic hand capable of mimicking a natural human hand is still a challenge (Ng, et al., 2021).Artificial arms and hands are being improved; however, they are not without issues regarding the learning curve and the actual costs of the devices (Biggar & Yao, 2015). A low cost and light weight (Jiang, et al., 2021) 3D printing of artificial arms can be a future solution to the issue; this would be a desirable solution to the people. However, there is a need of a system for the people with disabled upper limbs to assist them in computer usage specifically in underdeveloped and developing countries or for the people who are temporarily unable to use their fingers. Considering these facts, a system has been built for the people with upper limb disabilities in order to improve ease of usage and increase wider access to computers at a low cost (Khan, et al., 2019).

In this article, the developed computational model of the system is described and analyzed first. Then, the experimental results are corroborated with the theoretical ones. In order to improve the performance of the system, finally, the required conditions of the system and constraints for the keyboard are explained.

2. MATERIALS AND METHODS

The system development is presented in the next subsections.

2.1 Optical System

The system is designed and developed by utilizing the basic optical principle. The optical system consists of mirrors that make it convenient to maintain. Flexible mirrors in even numbers are inclined in specific angles which can be used to reflect the image of the keyboard in front of the user. Those mirrors are used to reverse the image and then make the keyboard appear normal or usual, creating what is known as a true image or real image(Naylor, 1970). Flexible mirrors made of plastics or polymers (acrylic plexiglass) are preferred over the glass to avoid the glass breaking hazard caused by the brittleness of the glass (Brostow, et al., 2011).

2.2 Design Description

A 2D view of the basic design of the optical system (Khan, et al., 2019) is presented in FIGURE 1.a. It indicates how the image of the keyboard is reflected and seen by a user. In this design, a keyboard is placed at the base of a desk. Two mirrors, Mirrors #1 and #2, are arranged at proper angles so that Mirror #2 can reproduce the image of the keyboard at the tabletop level; the equations for angle of the mirrors, θ, are developed and shown in the next section. It is worth mentioning here that an even number of mirrors can create a true image. FIGURE 1.b. shows a 2D view of the basic design of the proposed system with inclination angles and geometric positions of the mirrors. The user can view the keyboard in Mirror #2 as if it is at the location of

Mirror #2. In addition, owing to the location of Mirror #1, the position of the toes on the keyboard will be visible in Mirror #2.

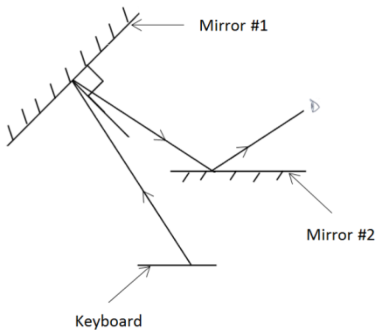

FIGURE 1.a: Basic 2D design of the optical system. The arrows show the direction of light from the keyboard to the eye. Mirror #2 is at the level of table top. The frame of the structure is not shown.

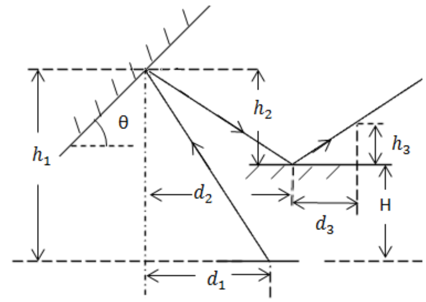

FIGURE 1.b: The figure shows the dimension of the design and angle of mirrors, θ, in FIGURE 1.a. H is the table height.

2.3 Theoretical Analysis

We utilize the basic optical principle to derive the governing equations of the design in FIGURE 1.b. They originate from the basic optical principles: the incident and reflected angles are equal, and the object and the image are equidistant from the reflecting plane (Sharma, 2006). As such, deductive method is followed to attain the final equations. The first equation is:

$$\frac{h_2}{d_2} = \frac{h_3}{d_3} \quad (1)$$

where, $\frac{h_3}{d_3}$ is the ratio of the height of the eye-level of the user from Mirror #2 and the location where a user wants to see the image. They can be selected based on the comfort of the user. Mirror #2 is assumed to be in horizontal position. At this condition, the height of Mirror #1 has been derived as:

$$h_1 = d_1 \tan\left(\pi - 2\theta - \tan^{-1}\left(\frac{h_3}{d_3}\right)\right) \quad (2)$$

where, $h_1 > H$ and H is the table height. Based on equation (2), h_1 can be obtained for the specified d_1, and $\frac{h_3}{d_3}$. The system is designed for these parameters. From the equation 2, angle between the mirrors, θ, can be calculated as:

$$\theta = \frac{1}{2}\left(\pi - \tan^{-1}\left(\frac{h_1}{d_1}\right) - \tan^{-1}\left(\frac{h_3}{d_3}\right)\right). \quad (3)$$

We performed some tests based on h_1, d_1, and $\frac{h_3}{d_3}$. Equation 3 was used to generate theoretical values of angle, θ, presented in TABLE 1. For the same angles, experiments determined the values of d_1. The results of the experiments along with theoretical values are shown in the table. The values of h_3 and d_3 in the table are only measured for their ratio;they do not represent the location of eyes with respect to Mirror #2.

H (inch)	h_1(inch)	d_3(inch)	h_3(inch)	θ (degree)	d_1(inch) (Theoretical)	d_1(inch) (Experimental)	% error
35.00	40.00	8.50	4.25	45.00	20.00	21.00	5.00
16.25	24.75	5.00	2.25	50.00	16.84	15.75	-6.47

TABLE 1: Comparison of theoretical and experimental data for d_1.

The parameter values shown in the table are measured from the experimental setup (Khan, et al., 2019). The deviation of experimental results from theoretical ones can be attributed to the measurement inaccuracies. The potential sources of error are in measuring $h_1$and the mirror angle, θ.However, from the table, one can infer that the system follows the model equation closely for the given constraints. The positive point about the deviation—from the theoretical one to the experimental one— for d_1 is that it can be adjusted for 1 to 4 inches from practical point of view.

For convenient use, the distance from the center of the seat to the middle of the keyboard is:

$$d = (d_2 + d_3) - d_1. \quad (4)$$

In the structure of the system, the positions of the keyboard and Mirror #2 need to be adjustable so that it can offer flexibility and comfort to the users.

Design Method:
How to Set Parameters in a Real Situation

2.4 Analysis of the Design Parameters: Exact Method

As there are multiple variables involved in the design, we assume some constant values for some of the variables for the design purpose. Assuming that the Mirror #2 is placed horizontally, the height $h_1$must be larger than H. The larger $h_1$will make the image depth in the Mirror #2 larger. The shorter height of Mirror #1, h_1, can produce a better image: The optical path should be as short as possible. While keeping the mirrors in a fixed place, the position of the keyboard can be relocated for the convenience of viewing it in Mirror #2.
The first derivative of the equation 2 is:

$$\frac{dh_1}{dh_3} = d_1 sec^2[(\pi - 2\theta - \tan^{-1}(\frac{h_3}{d_3}))]\,(-\frac{1}{1+\left(\frac{h_3}{d_3}\right)^2})(\frac{1}{d_3}). \quad (5)$$

For the convenience of design, θ can be selected as 45°. For a smaller value of h_3, 0-3'', even a small inaccuracy in measuring can lead to a large error for h_1 as indicated by equation 5 and shown in FIGURE 2. A large h_3 is, therefore, desired to reduce design error for h_1.

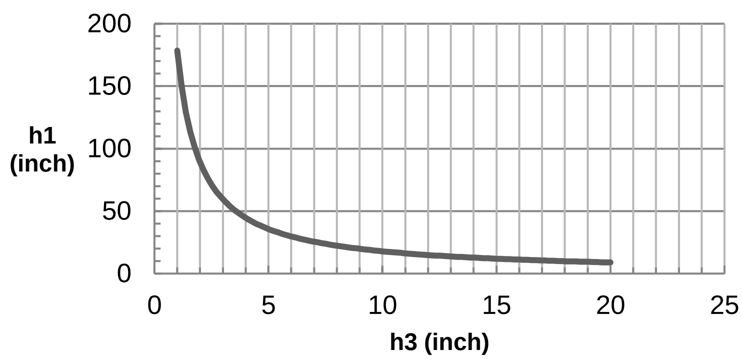

FIGURE 2: Variation of h_1 with h_3.

For the system design, h_1 is an important parameter related to the space occupied by it. As stated earlier, it must be greater than H to produce a suitable image in Mirror #2. FIGURE 3 indicates a region of operation where the system can function for the given constraints. It can be noted that the peak value of h_1 is not a factor for the design, and there is a functional discontinuity at that point. However, the blue line above the red line is the region of operation for the system. For a better image, the gap $\mathrm{d} = \mathrm{h}_1 - \mathrm{H}$ can be as large as the width of Mirror #1 as it has been observed.

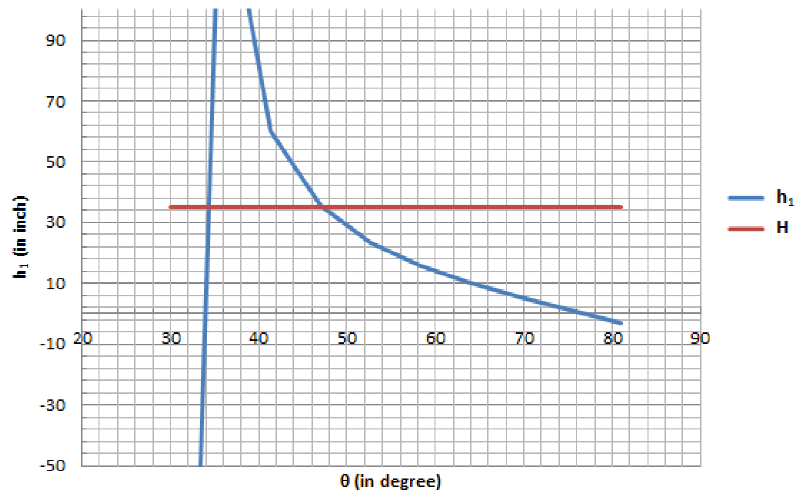

FIGURE 3: Variation of the height of Mirror#1, h_1, with θ, the inclination angle of Mirror#2 for $d_1 = 21$ and $\frac{h_3}{d_3}$=0.5. With the increase of $\frac{h_3}{d_3}$, the peak point shifts toward the left, a smaller θ.

The range of d_3 can be made variable with a wide mirror. In this study, the mirror was 12 inch wide. The image can be formed along and within that dimension. A wider mirror can provide flexibility of viewing the keyboard for a user. While keeping all the parameters constant, a user can move toward or away from the system or move the head up or down while one can still see the image provided that the mirror is wide.

2.5 Data Matrix

As shown in TABLE 1, the theoretical results are validated by the experimental ones. The other theoretical data matrices about mirror positions, and inclination angle are generated and listed in TABLE 2 since they are critical parameters of the system design. The data presented in the table are for two table heights: H=35 inch and H=16.25 inch. The following table presents the functional parameter values for the system.

Data number	d_1 (inch)	$\frac{h_3}{d_3}$	h_1 (inch)	H=35 inch	H= 16.25 inch		Data number	d_1 (inch)	$\frac{h_3}{d_3}$	h_1 (inch)	H=35 inch	H= 16.25 inch
1	14	0.25	56.00	✓			25	19	0.250	76.00	✓	
2		0.37 5.00	37.33		✓		26		0.375	50.67	✓	
3		0.50	28.00		✓		27		0.500	38.00		✓
4		0.62 5.00	22.40				28		0.625	30.40		✓
5	15	0.25	60.00	✓			29		0.750	25.33		✓
6		0.37 5.00	40.00	✓			30	20	0.250	80.00		

7		0.50	30.00		✓		31		0.375	53.33	✓	
8		0.62 5.00	24.00		✓		32		0.500	40.00	✓	
9	16	0.25	64.00	✓			33		0.625	32.00		✓
10		0.37 5.00	42.67	✓			34		0.750	26.67		✓
11		0.50	32.00		✓		35		0.875	22.86		✓
12		0.62 5.00	25.60		✓		36	21	0.250	84.00		
13		1.00	16.00				37		0.375	56.00	✓	
14		1.12 5.00	14.22				38		0.500	42.00	✓	
15	17	0.25	68.00	✓			39		0.625	33.60		✓
16		0.37 5.00	45.33	✓			40		0.750	28.00		✓
17		0.50	34.00		✓		41		0.875	24.00		
18		0.62 5.00	27.20		✓		42	22	0.250	88.00		
19		0.75	22.67				43		0.375	58.67	✓	
20	18	0.25	72.00	✓			44		0.500	44.00	✓	
21		0.37 5.00	48.00	✓			45		0.625	35.20		✓
22		0.50	36.00		✓		46		0.750	29.33		✓
23		0.62 5.00	28.80		✓		47		0.875	25.14		✓
24		0.75	24.00		✓		48		1.000	22.00		

TABLE 2. A table of theoretical results for θ=45° and other constraints: reasonable H and d_1.

Note: The tick mark, ✓, indicates that the related parameter values can produce an effective system. However, the other values can produce image, but they are not practical since a large h_1 can make image depth in Mirror #2 large. For example, data 36 and 42 will not produce an effective system for H=35 inch.

Some other convenient design matrices are shown in Appendix A. The results in the tables indicate that only some values of $\frac{h_3}{d_3}$ produce an effective system for a given table height, whereas others do not. However, the movement of a user is expected while using a computer; hence a range of $\frac{h_3}{d_3}$ should be considered for a user-friendly design. The results presented in this article are, therefore, useful for the system design. Future developers of the system can utilize the theoretical parameters, shown here, based on the user constraints.

Only the correct values of the above design parameters may not ensure the optimum operation of the system; the ambient condition plays a role for the clear view of the keyboard as observed. Importantly, the size and the color contrast of the keys are the other critical factors for the design. These aspects are discussed in the next sections with more test results.

2.6 Analysis of the Design Parameters: Approximate Method

This method uses the following equation:

$$d_2 = \frac{(h_1 - H)d_3}{h_3} \quad (6)$$

with the condition thatd_1 and d_2 values are close.In this method, $d_1$is assumed to be equal to d_2; this implies that the horizontal distance of the keyboard from the center of the chair is equal to the distance from Mirror #2 to the center of the chair. In the next step, the convenient figure for H is chosen.

For simplicity, the value of θ can be selected as 45°. The ratio of $\frac{h_3}{d_3}$ should be based on the comfort of the user. This will produce the value of d_1.

After following the approximate method, the adjustment for $d_1$is convenient. While adjustingd_1, it needs to ensure that it is convenient for the user.

2.7 Designed System

The developed system, shown in FIGURE 4, consists of two plastic mirrors (see FIGURE 1 and 2), one keyboard with a high color contrast of the keys. An image of the early system with a keyboard, its reflected image, and a monitor is presented in FIGURE 4. The vertical distance between the position of the reflected image and the monitor is relatively small. A user, therefore, can see the keyboard in front of the monitor with ease.

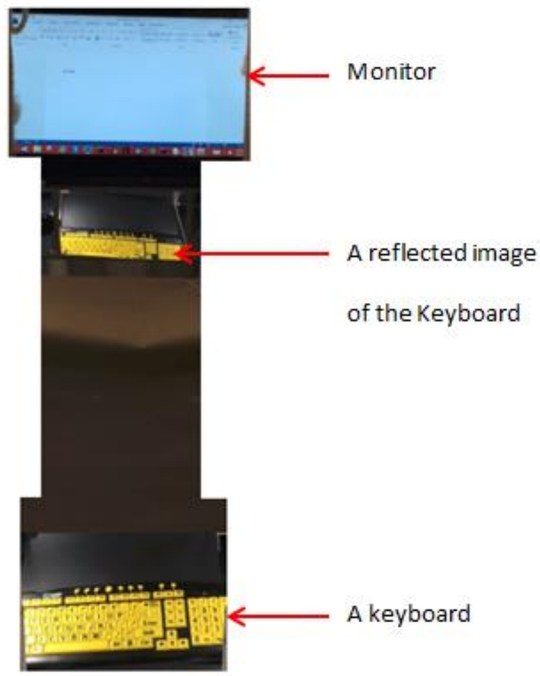

FIGURE 4: Image is showing keyboard, its image, and the monitor. The keyboard was lit by two LED light sources as shown in FIGURE 5. Since the monitor and the reflected images are not in the same image plane, they are not in the focus for the camera used (Khan, et al., 2019).

In the designed system, a keyboard is located at the base of the desk. Two LED light sources are positioned on the two sides of the keyboard so that they can fully illuminate the keyboard when the room is dark. Since the LED light sources consume relatively low energy and dissipate less heat, the temperature of the keyboard will not be uncomfortable for the user's foot.

2.8 Light Sources and Illuminance Level

Two LED light sources were added to provide ample light to make the keyboard properly visible. In this work, the illuminance level on the keyboard was approximately 147 lux on the average. Each LED light source utilized has 3.5 Watt power. The positions of the light sources are shown in FIGURE 5. The light sources are positioned 11 inches above the surface of the keyboard. However, in a lit room with an average luminance level of 285 lux, no LED light source was required as shown in the next section. Note that the illuminance level was measured at table height.

3. TEST RESULTS

The functionality of the system was tested under two lighting environments, and with different types of keyboards.

3.1 With LED Light Sources

Tests were performed with keyboards of different key colors and sizes. During all tests, the position of the LED light sources was kept fixed. Because of the reflections by the mirrors, the size of the keyboard letters appeared smaller than the actual size. For that reason, a keyboard with large letters must be considered or magnification of the small letters of the keyboard is required. It has been observed that after two reflections, the letters of several keyboards appear to be almost unrecognizable. This fact is illustrated in FIGURES 6 and 7.

FIGURE 5: An image of the keyboard in a dark room with two LED light sources.

FIGURE 6: A reflected image of the keyboard with regular size white letters on black background. The letters are almost unrecognizable.

The keyboard seen in Mirror #2, shown in FIGURE 6, is a typical keyboard with white small letters on black background. FIGURE 7 shows the image of another keyboard (Azio Vision, 2025) in front of the user. The keys of the keyboard are LED back lit; they can emit pink, blue, red and pale yellow colors for the keys. The keyboard has thicker and larger letters compared to those of a typical keyboard.

FIGURE 7: A reflected image of the keyboard with pink letter color.

The study showed that Azio keyboard did not yield the expected outcomes regarding visibility and legibility of the keyboard letters as they were not well visible for any of the colors. This is attributed to the low color contrast. The result of only pink colored letter keyboard is shown in FIGURE 7.

As the keys were not well visible, the color contrast factor was taken into consideration; literature indicates how color contrast can influence readability. Studies showed that high color contrast can be achieved by using black text on a yellow or light yellow background (Luckiesh, 1921; Rello & Yates, 2012; Wu & Yuan, 2003; Scharff, et al., 1999). By using a high contrast keyboard with large letters, we were able to improve the visibility and legibility of the keyboard letters. We performed tests with black letters on a yellow background Large Print, Low Vision, Ergonomic Multi-Media Keyboard with Low-Profile Yellow Keys (EZsee, 2025) as shown in FIGURE 8.

FIGURE 8: A reflected image of the keyboard with high contrasting letters color and large letters.

FIGURE 9 indicates that keyboards with high color contrast and large letters are essential for this design. The brightness of the lit environments was the same for FIGURES 6-8; however, the keys are not well visible in these images (see FIGURES 6 and 7). At this point, one can conclude that the best results for visibility and legibility can be obtained from the keyboard with black letters on a yellow background.

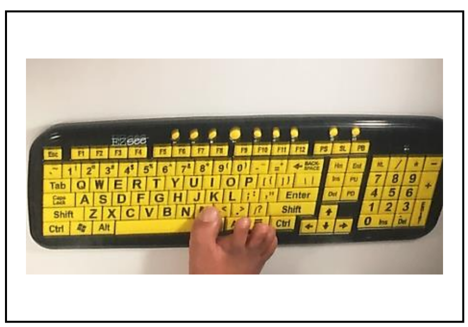

FIGURE 9: Toe is pressing the letter 'M'. The image is a reflected image that appears in front of the user. The keyboard was lit by the LED light sources(Khan, et al., 2019).

3.2 Without LED Light Sources

Experiments were also performed at room lighting condition with the keyboards that are not lit by the LED light sources. The reason for these experiments was to determine whether the system can function in a well or partially lit room. We found that a high contrast keyboard with large letters yields better results in this case, see FIGURE 10, at tabletop illumination level of 285 lux. At this point, one can conclude that the system works well under lighting conditions in a lit room.

FIGURE 10: The reflected image of a high contrast keyboard with large letters. All the letters are visible and easily recognizable in the reflected image. The room light source is located on the left side of the keyboard; this is why, the left side of keyboard looks brighter than the right.

Even though the keyboard is visible in the room lighting environment, the LED light sources are suggested for better visibility.

3.3 Limitation of the design

The main limitation of the system is that the optical system components will require adjustability for the people with different lengths of legs and trunks. For example, adjustments in the positions and angles of the mirrors will be required for the children with the disability. In this case, the system can still be designed with the developed equations; however, the drawbacks of this adjustability are the added components and cost. Along with the designed keyboard, a foot-operated mouse can be included for complete access to a computer.

4. DISCUSSION

The study results show that the analytical model matches the experimental results closely. Utilizing the developed equations, a system can be designed for any table heights, implying that the system can be used by people with differing trunk lengths. As there are no known model equations for the system (Khan, et al., 2019), the proposed model not only does offer systematic equations but also does scalability. For example, the experimental results obtained for H=16.25 and 35 inches which are presented in TABLE 1. The system can also be designed for people with different trunk lengths which is indicated by the parameter H. Equations 1-3can be utilized to design the system for a particular individual with the constraint of $d_1 > H$.A plot, similar to FIGURE 3,generated by the equations for $d_1$and $\frac{h_3}{d_3}$ as variables can guide a functional design.

The future work for the system will focus on users' body proportions and varying test conditions such as environmental lighting. The spaciousness is one limitation of the current design; the future study will, therefore, address the compactness of the design as well.

5. SUMMARY

The article addresses the question on how to develop a system and corresponding analytical model of a low cost accessibility tool for the people with upper extremity disability in developing countries. It focused on the technological development of a low-cost optical system which can have potential use in computer access for the people with the disabled limbs. In the absence of governing equations of the system, time extensive trial and error method can be utilized. The equations developed for the system can provide guidelines in designing it for given constraints. It will also offer flexibility in design as the parameters are variables. Given any table height, H, the system can be analyzed employing the equations developed.

It has been shown that the system can function in a lit room illuminated at 285 lux, requiring no additional light source. Important aspects of the design are its simplicity and utilization of easily available materials such as mirrors and high color contrast keyboard. Self-maintenance of the system is another important feature of the design and can further reduce the cost of it for a long-term use.

In this study, the design parameters for the optical system are obtained from both simulation and experiments. The test results, presented in images, validate the functionality of the system for the given constraints with the emphasis on the fact that the keyboard image can be displayed at tabletop level. Now this study can be considered as the beginning point of the future study focusing on performing target user evaluation on the system.

The optical system designed occupies considerable space. Therefore, it could be accommodated in homes; however, in an academic setting, it may not be accommodated unless there is a dedicated space. It can also be accommodated in rehabilitation centers. The practical usage of the proposed system is expected to enhance computer access at low cost for the people with the disability. The access to computer can direct to educational opportunity as well as jobs resulting in personal and economic freedom.

6. PATENTS

In the context of the system design, one disclosure of invention was submitted to Jackson State University, Jackson, MS.

Funding: This research received no external funding.

Acknowledgments: The authors like to thank the ECE department of Saginaw Valley State University and ECECS department of Jackson State University. They also thank Ms. Ursla-Marie Offiah for prior data collection.

Conflicts of Interest: The author(s) declared no potential conflict of interest with respect to the research, authorship, and/or publication of this article.

Appendix A

TABLE 3: A table of theoretical results for θ =40° and other constraints: reasonable H and d_1.

Data number	d_1 (inch)	$\frac{h_3}{d_3}$	h_1 (inch)	H=35''	H= 16.25''		Data number	d_1 (inch)	$\frac{h_3}{d_3}$	h_1 (inch)	H=35''	H= 16.25''
1	14	0.375	75.127	✓			33	19	0.375	101.9581		
2		0.5	47.0669	✓			34		0.5	63.8765	✓	
3		0.625	34.6418		✓		35		0.625	47.0139	✓	
4		0.75	27.6315		✓		36		0.75	37.4999		✓
5		0.875	23.1296		✓		37		0.875	31.3901		✓
6	15						38		1	27.1348		✓
7		0.375	80.4933	✓			39		1.125	24.0009		✓
8		0.5	50.4288	✓			40	20	0.5	67.2384	✓	
9		0.625	37.1163		✓		41		0.625	49.4883	✓	
10		0.75	29.6052		✓		42		0.75	39.4735	✓	
11		0.875	24.7817		✓		43		0.875	33.0422		✓
12							44		1	28.563		✓
13	16						45		1.125	25.2641		✓

14		0.375	85.8595				46		1.25	22.7333		✓
15		0.5	53.7908	✓			47	21	0.5	70.6004	✓	
16		0.625	39.5907		✓		48		0.625	51.9628	✓	
17		0.75	31.5788		✓		49		0.75	41.4472	✓	
18		0.875	26.4338		✓		50		0.875	34.6944		✓
19		1	22.8504		✓		51		1	29.9911		✓
20	17						52		1.125	26.5273		✓
21							53		1.25	23.87		✓
22		0.5	57.1527	✓			54	22	0.5	73.9623	✓	
23		0.625	42.0651	✓			55		0.625	54.4372	✓	
24	17	0.75	33.5525		✓		56		0.75	43.4209	✓	
25		0.875	28.0859		✓		57		0.875	36.3465		✓
26		1	24.2785		✓		58		1	31.4193		✓
27	18	0.5	60.5146	✓			59		1.125	27.7905		✓
28		0.625	44.5395	✓			60		1.25	25.0067		✓
29		0.75	35.5262		✓		61		1.375	22.8035		✓
30		0.875	29.738		✓							
31		1	25.7067		✓							
32		1.125	22.7377		✓							

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