

Design and Implementation of a Smart Wireless Controlled Visual Acuity Measurement System

Abstract

In this article, a smart visual acuity measurement (VAM) system is designed and implemented. Hardware of the proposed VAM system consists of two parts: a wireless remote controller, and a high-resolution LCD controlled through a Raspberry-Pi mini-computer. In the remote controller, a 3.5" graphical LCD with a touch screen is used as a human-machine interface. When a point is pressed on the touch screen, the unique identifier (ID) code of that point as well as its page number is transmitted to the Raspberry-Pi. In the Raspberry-Pi, data are received and processed by a smart application coded in visual studio software. Then, the commanded tasks are executed by the Raspberry-Pi's operating system. Numerous charts, characters, and pictures are stored in the proposed VAM system to provide various VAM options while the size of the optotypes is adjusted automatically based on the distance of the patient from the LCD. The performance of the proposed VAM system is examined practically under the supervision of an expert optometrist where the results indicate that visual acuity, astigmatism, and color blindness of patients can be examined precisely through the proposed VAM system in an easier and more comfortable manner.

Keywords: LCD E-chart, Raspberry-Pi, visual acuity, visual acuity measurement, wireless communication network

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Introduction

Visual acuity is the clarity or sharpness of vision. Often, charts with different types of characters are used to measure the visual acuity of persons. By using these charts, the patient's ability to recognize small characters with precision is assessed and the final result is presented as a fractional number like 20/100 that expresses the rate of the patient's visual acuity.^[1]

20/20 vision is a fractional number used to express normal visual acuity measured at a distance of 20 feet, i.e., a person with 20/20 visual acuity can see clearly at 20-feet what should normally be seen at that distance. However, 20/100 visual acuity means that the patient must be as close as 20-feet to see what a person with normal vision can see at 100 feet.^[2]

Expressing the visual acuity by a fractional number is proposed in 1861 by F. C. Donders.^[3] He proposed a formula that expresses the "sharpness of vision" in

terms of the ratio of the letter size to the viewing distance. One year later, H. Snellen publishes the first visual acuity chart based on the Donders's suggestion. Snellen designs special characters, called optotypes, and arranges them in a chart format to be used as a tool for visual acuity examination.^[4]

In 1888, E. Landolt proposes the broken ring symbol for visual acuity examination. Although the Landolt's chart becomes a standard tool for laboratory testing, it gets limited popularity in clinical tests.^[5]

In 1959, L. Sloan designs a new set of letters and arranges them in a rectangular format to provide a visual acuity measurement (VAM) chart. Moreover, he introduces the term "M-unit" to simplify the procedure of character size adjustment in visual acuity charts reproduction.^[6]

In 1976, Bailey and Lovie propose a new layout with proportional spacing and five letters on each line. By doing so, a chart in the form of an inverted triangle is created, rather than the rectangular format used by

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L. Sloan. Moreover, they introduce the term logMAR to describe the logarithmic progression of the chart lines more easily.^[7]

In 1982, the National Eye Institute (NEI) combines the Sloan letter set with the Bailey-Lovie layout to produce the first large, multi-center clinical trial chart for use in the Early Treatment of Diabetic Retinopathy Study (ETDRS).^[8] Since NEI performs all later clinical studies through ETDRS charts, ETDRS format with the logarithmic progression becomes the most popular chart format for visual acuity examination.^[9]

VAM system is a useful tool in refractive correction; that is, based on the results of the visual acuity examinations, it can be deduced that which lens is better for a person. Moreover, VAM system is an easy and low-cost tool to detect abnormal visual status. However, to obtain more information about the patient's status, other devices such as slit lamp and ophthalmoscope can be used.^[10]

Nowadays, microprocessors and single-board computers (SBCs) are widely used in the implementation of smart equipment. By programming the visual acuity examinations into an SBC, a smart VAM system is achieved that can assess the visual acuity of patients in an easier and more precise manner. Moreover, numerous charts can be stored in the memory of the SBC to enhance the performance of the VAM system. On the other hand, due to the existence of a high-performance processor, the examination parameters can be adjusted easily based on the optometrists' requirements.

The SMART LC 13-LCD visual chart made by Medizs Inc. is an example of smart VAM systems which consists of a 13 inches LCD and an Infrared (IR) remote controller. In SMART LC 13, various charts with different optotypes are used to extend the application of the VAM system. However, SMART LC 13 suffers from two shortcomings:

- i. Since data are transferred from the remote controller to the LCD through IR transmitter, remote controller must be placed directly in front of the LCD such that no obstacle stays in front of the IR light ray; otherwise, the transmitted data cannot be received properly by the LCD. This shortcoming reduces the operating range of the remote controller
- ii. Due to the unidirectional data communication between the remote controller and LCD, the LCD cannot send any data or acknowledgment to the remote controller. As a result, it cannot be identified whether the transmitted data are received properly by the LCD.

The CC-100 LCD visual acuity chart made by Topcon Inc. is another example of smart VAM systems that consists of a 21.5 inches LCD and an IR remote controller. The CC-100 VAM system can be operated in two ways: (i) stand-alone operation in which the LCD is controlled through the IR remote controller; and (ii) operation through

the CV-5000S PC controller software in which the VAM system is combined with Topcon's dedicated CV-5000PRO automated phoropter. Although combining CC-100 with CV-5000PRO extends the applications of this VAM system, it still suffers from the two shortcomings, above, that are arise from the IR remote controller.

To overcome the shortcomings, above, in this article, a smart VAM system is designed and implemented to provide the following advantages compared to the conventional VAM charts and previous smart VAM systems: (i) data are transferred in a bidirectional manner between the remote controller and the LCD through a secure Wi-Fi network, (ii) numerous charts with different optotypes can be stored in the memory of the proposed digital VAM system; hence, optometrists can select the best chart based on the patient status; (iii) optotypes can be arranged in various chart formats; (iv) apart from visual acuity examinations, astigmatism, and color blindness of the patients can be examined easily; (v) optotypes are resized by the software based on the distance specified by the optometrist; and (vi) a more accurate and more concise diagnosis is ensured.

The details of the design and implementation of the proposed VAM system are presented in detail in the following sections: hardware of the proposed VAM system is introduced in section II; the wireless network used in the proposed VAM system are presented in section III; software of the proposed VAM system is introduced in section IV; the visual acuity examination charts stored in the proposed VAM system in addition to the applications of each chart in optometry are introduced in section V. Experimental evaluation of the proposed VAM system is presented in section VI and conclusion is presented in section VII.

Hardware of the Proposed Visual Acuity Measurement System

Hardware of the proposed VAM system consists of two parts: (i) a controller for the main LCD and (ii) a remote controller. In the following two subsections, each part is introduced in detail.

Main LCD controller

This part of the proposed VAM system consists of the following four parts: (i) a Raspberry-Pi SBC to manage and control the main LCD screen, (ii) an interface board to extend the Raspberry-Pi general-purpose input/output (GPIO) pins, (iii) an interface board to power ON/OFF the device, and (iv) an interface board to convert HDMI video output of the Raspberry-Pi to LVDS video output.

In the following paragraphs, each part of the main LCD controller is introduced in detail.

Raspberry-Pi

In the proposed VAM system, a Raspberry-Pi 4B is used to perform the following tasks: (i) receiving data from the

wireless network, (ii) processing the received data and identifying the necessary tasks commanded by the user, and (iii) performing the desired tasks including the setting of the required parameter as well as the management of the content of the main LCD screen.

To perform the tasks, above, an application is coded in Visual Studio software and then a Linux-compatible version of the application is generated. In the next step, the prepared application is transferred to the memory of the Raspberry-Pi and run at the startup time of the Raspberry-Pi's operating system. Details of the prepared application will be presented in *section III*.

Based on the recommendations of the Raspberry-Pi manufacturer,^[11] proper fan and heatsink must be used to avoid overheating of the Raspberry-Pi's processor. To do this, powerful fans and heatsink are shown in Figure 1 are attached to the raspberry-pi board where the results reveal that the processor temperature decades about ten degrees of centigrade after attaching the fan and heatsink.

Raspberry-Pi's general-purpose input/output extension board

In the proposed VAM system, an extension board [Figure 2] is used to connect the Raspberry-Pi's GPIO pins to the external devices used in the main LCD controller. These external devices are an ESP8266 module, a buzzer, a LED, a three-state buffer/line driver, and eight optocouplers.

In the designed extension board, the ESP8266 module is adopted to implement a wireless network for bidirectional data communications. The receiver and transmitter (RX and TX) pins of ESP8266 module are connected to UART0_TXD and UART0_RXD pins (GPIO14 and GPIO15) of the Raspberry-Pi, respectively, while VCC and GND pins of the ESP8266 are connected to 3V3 and ground pins of the Raspberry-Pi, respectively.

After each successful data reception in the Raspberry-Pi, one pulse with 100-ms time duration is applied to the buzzer and LED to generate a beep and a LED blinking, respectively. In the proposed extension board, GPIO1 and GPIO12 of the Raspberry-Pi are amplified by 74HC245 line driver and then are applied to the buzzer and LED, respectively. Furthermore, GPIO20 pin is used to turn ON/OFF the main power of the proposed VAM system while GPIO21 is used to turn ON/OFF the power of the main LCD. Both of these two pins are amplified by 74HC245 line driver, isolated by two independent optocouplers, and then applied to the power ON/OFF control board of the system.

Power turn ON/OFF control board

In the proposed VAM system, a control board is designed to manage power ON/OFF the system [Figure 3]. In this board, two independent relays are parallelized to control

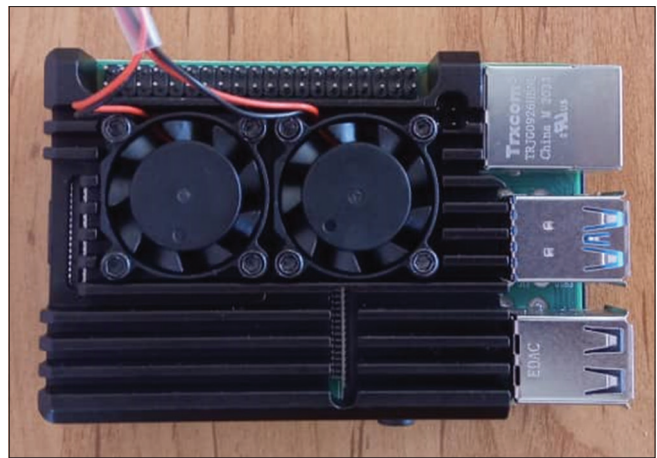


Figure 1: Fan and heatsink used to avoid overheating of Raspberry-Pi

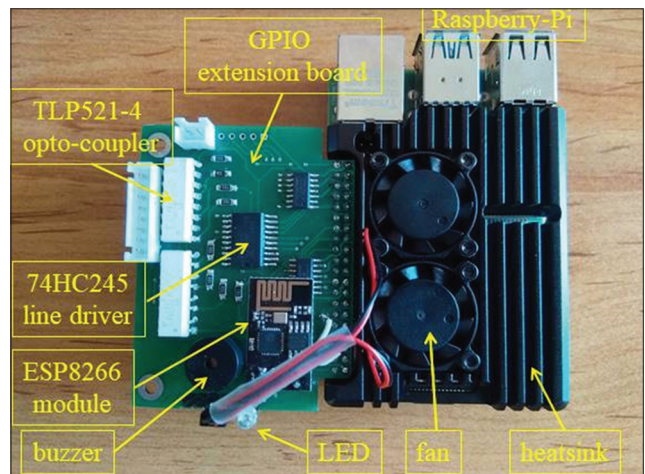


Figure 2: Raspberry-Pi extension board

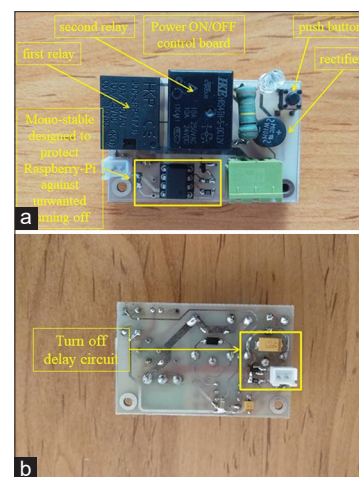


Figure 3: Power turn ON/OFF control board: (a) Top view, (b) Bottom view

the power path. To power ON the system, the push button provided on the main LCD's body must be pressed. By doing so, the first relay is activated for about ten seconds to create a path for the main power of the system. During this time interval, Raspberry-Pi is powered on and activates the second relay; hence, another path is created for the

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main power of the system and the first relay can be turned off without any problem.

After turning on the proposed VAM system, to protect Raspberry-Pi against unwanted turn off, turn-off process can only be triggered by the remote controller. To do this, a Bistable Multivibrator is used in the power ON/OFF control board.

To turn off the main power of the system, the power off icon provided on the first page of the remote controller must be touched. By doing so, the unique code dedicated to the turn-off icon is transmitted to the Raspberry-Pi. Each time Raspberry-Pi receives this code turns the second relay of the power control board off and cut off the main power path of the system.

Since a small time interval is required to close the applications and hang up the operating system, the second relay cannot be turned off immediately. Therefore, a simple delay circuit consists of one NPN transistor, one resistor, and one capacitor is added to the ON/OFF control board to generate the necessary delay. By doing so, the second relay is turned off five seconds after polling down the GPIO20 pin of the Raspberry-Pi.

HDMI to LVDS converter board

In the proposed VAM system, a 1280*1024 pixel LVDS-compatible LCD is used to show optotypes for visual acuity examinations. Since Raspberry-Pi 4 supports only two mini-HDMI video outputs, an interface board [Figure 4] is used in the proposed VAM system to convert the HDMI output of the Raspberry-Pi to LVDS video output.

Remote controller

This part of the proposed VAM system consists of the following four parts: (i) a graphical LCD (GLCD) used as human-machine interface (HMI), (ii) a microcontroller-based board used as an interface between the HMI and ESP8266 module, (iii) a lithium-polymer battery used as a power supply, and (iv) a power

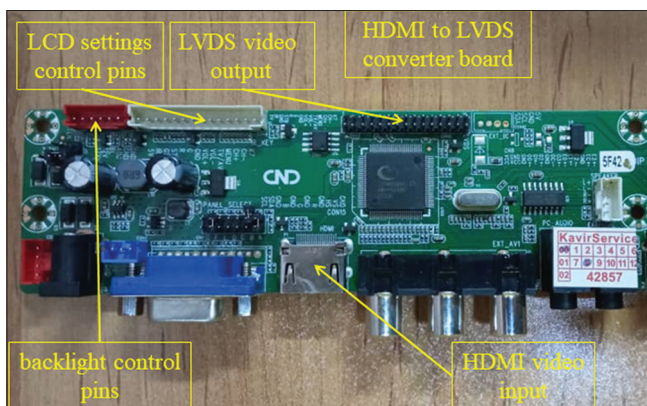


Figure 4: HDMI to LVDS converter board

management module used as a lithium-polymer battery charger.

In the following paragraphs, each part of the remote controller is introduced in detail.

Graphical LCD

A 3.5" GLCD with a resistive touch screen is used as HMI in the proposed remote controller. Various pages with different icons are designed for the GLCD where each page is dedicated to specified purposes, for example, page 1 is the main menu, page 2 is dedicated to chart type selection, page 3 is dedicated to settings, page 4 is dedicated to arrow keys used to change the content of the main LCD screen.

All the designed pages are stored in the memory of the GLCD. Whenever an icon is touched on the GLCD, the unique code of that icon which consists of four bytes (header byte, icon ID, page number, and footer byte) is transferred to the Raspberry-Pi. At the same time, the relevant page of the pressed icon is loaded on the GLCD screen. The top view of the GLCD as well as some of the designed pages is illustrated in Figure 5.

Interface board between human machine interface and ESP8266 module

To send data through an ESP8266 module, a predefined sequence of commands must be sent to the module. Since the GLCD cannot send these commands to the module directly, an interface board [Figure 6] containing an STM32 microcontroller is placed between the HMI and ESP module. All data packets generated by the HMI are received and processed by the microcontroller and then are transferred to the ESP8266 module through a serial port of the microcontroller. ESP8266 module receives data from the microcontroller, eliminates redundant bytes, extracts useful data packets, and transfers them to the ESP8266 module placed in the Raspberry-Pi side.

The details about the commands transmitted to the ESP8266 module to send a message are presented in section III.

In the proposed interface board, a voltage of the lithium-polymer battery used as the power supply is monitored continuously through an ADC channel of the microcontroller. After each ADC conversion, the state of charge of the battery is calculated according to the ADC conversion result and the characteristic curve of the battery.

To protect the battery against over-discharging, whenever the voltage of the battery decodes to a value smaller than 3.8V, a red LED is turned on to inform the user; furthermore, whenever the voltage of the battery is reduced below 3.7V, the remote controller is turned off automatically.

Lithium-polymer battery and its charger module

The power of the remote controller is supplied by a 1500 mAh lithium-polymer battery. A full-charge voltage

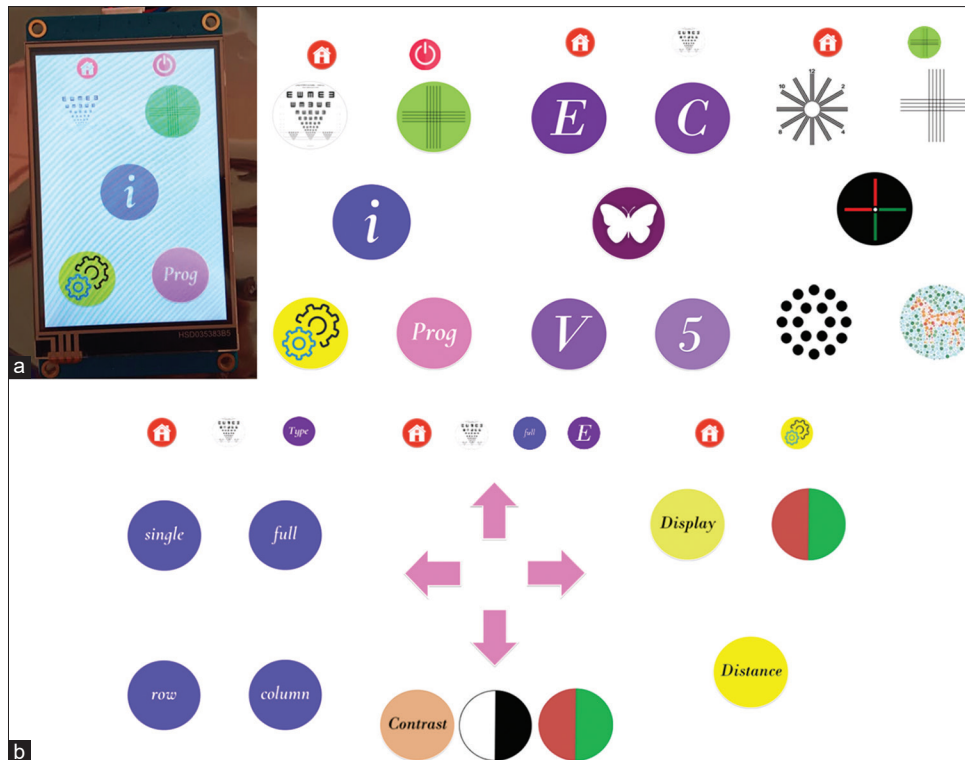


Figure 5: (a) 3.5" GLCD used as a HMI, (b) some of the pages designed for the GLCD. HMI: Human machine interface

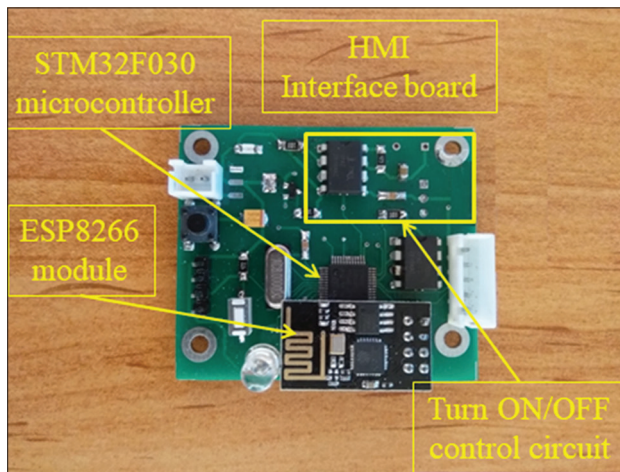


Figure 6: HMI interface board

of the battery is 4.2 V while to protect the battery against over-discharging, voltages below 3.7 V must be avoided; hence, the voltage of the battery is not constant and varies between 3.7 V to 4.2 V. However, the STM32 microcontroller and ESP8266 module require a fixed 3.3V supply voltage for proper operation. Therefore, a low dropout voltage regulator (LDO) is used in the HMI interface module to fix the supply voltage to 3.3 V.

According to the recommendations of the battery manufacturer, a fixed voltage of 4.2 V is required to charge the lithium-polymer battery. Since 5V adaptors and USB chargers are widely accessible, another LDO is used in the remote controller to receive a 5V supply from a mini USB

port and provide a fixed 4.2 V to charge the battery. By doing so, the proposed remote controller can be charged through a common 5V charger.

The lithium-polymer battery used in the remote controller as well as its charger module is illustrated in Figure 7.

Finally, the proposed VAM system is implemented in practice where its picture is illustrated in Figure 8.

Wireless Network of the Proposed Visual Acuity Measurement System

As mentioned earlier, in the proposed VAM system, two ESP8266 modules are used to create a wireless network for bidirectional data communication between the remote controller and the main LCD controller. In this network, the main LCD controller acts as a server while the remote controller is configured as a client.

To use the ESP8266 modules, at first, their firmware must be updated, and then each ESP8266 module must be configured properly through the AT-Commands introduced by Espressif Systems Company.^[12] To do this, AT-Commands tabulated in Table 1 are transmitted sequentially by the Raspberry-Pi to the first ESP8266 module to configure it as a server while AT-Commands tabulated in Table 2 are transmitted sequentially by the STM32 microcontroller to the second ESP8266 module to configure it as a client.

After the successful configuration of both ESP8266 modules, data can be transferred between them in a

Table 1: AT-commands transmitted to the ESP8266 module to configure it as a server

AT-command	Decimal ASCII code of the command
AT + RST	65,84,43,82,83,84,13,10
AT + CIPMODE=1	65,84,43,67,87,77,79,68,69,61,49,13,10
AT + CWSAP="SSID","PASS", ID, CH	65,84,43,67,87,83,65,80,61,34,'S','S','I','D',34,44,34,'P','A','S', 'S',34,49,48,13,10
AT + CIPMUX=0	65,84,43,67,73,80,77,85,88,61,48,13,10
AT + CIPSERVER=1, PORT	65,84,43,67,73,80,83,69,82,86,69,82,61,49,44,54,54,54,54,13,10

ASCII – American Standard Code for Information Interchange

Table 2: AT-commands transmitted to the ESP8266 module to configure it as a client

AT-command	Decimal ASCII code of the command
AT + RST	65,84,43,82,83,84,13,10
AT + CIPMODE=0	65,84,43,67,87,77,79,68,69,61,48,13,10
AT + CWJAP="NAME","PASS","BSSID","PCI-EN"	65,84,43,67,87,74,65,80,61,34,'S','S','I','D',34,44,34,'P','A','S', 'S',34,49,48,13,10
AT + CIPMUX=0	65,84,43,67,73,80,77,85,88,61,48,13,10
AT + CIPSTART=ID,"Type","IP", PORT	65,84,43,67,73,80,83,84,65,82,84,61,48,44,34,84,67,80,34,44,34,49,57,50,46,49,54,56,46,52,46,49,34,44,54,54,54,54,13,10

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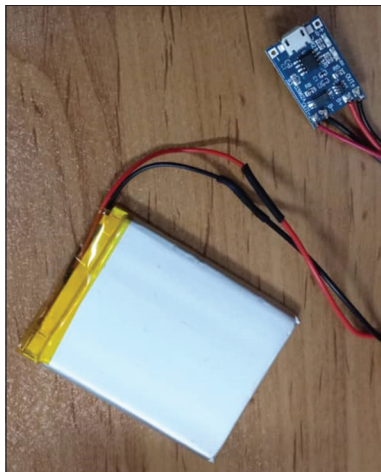


Figure 7: Lithium-polymer battery and its charger module



Figure 8: The implemented VAM system. VAM: Visual acuity measurement

bidirectional manner using the AT-commands as tabulated in Table 3.

To check the wireless connection between two modules, after each data reception, the receiver module sends an acknowledgment packet to the transmitter. If the transmitter module does not receive any acknowledgment packet, sends previous data packet again and checks the connection status. Receiving no acknowledgment packet after two consecutive transmissions means that the wireless network is not reachable; hence, the message of “waiting for connection” [Figure 9] is loaded on the remote controller to inform the user. At the same time, both the server and client try to reconnect to the wireless network.

Software of the Proposed Visual Acuity Measurement System

As mentioned earlier, in the proposed VAM system a Raspberry-Pi is used to manage the main LCD screen to

perform various visual acuity examinations. Moreover, an STM32 microcontroller is used in the remote controller to transmit the user commands to the main LCD controller. In this section, the programs prepared for each part of the proposed VAM system are introduced in detail.

C# application programmed into the main LCD controller

In the proposed VAM system, a graphical user interface (GUI) application is coded in C# language in Microsoft Visual Studio Enterprise software. Visual Studio software has the capability of generating executable application files for Linux-based operating systems. By using this feature, although the GUI application is coded in C#, it can be run on the Raspbian operating system of the Raspberry-Pi which is a Linux Debian-based operating system.^[13]

In the proposed GUI application, at first, GPIO pins of the Raspberry-Pi are configured properly while the ESP8266

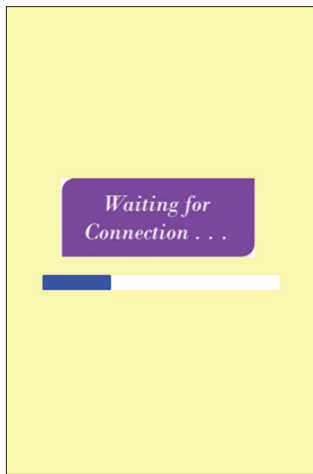


Figure 9: “Waiting for connection” page

Table 3: AT-command transmitted to the ESP8266 module to send the “MESSAGE”

AT-command	Decimal ASCII code of the command
AT + CIPSEND=ID, number of bytes	65,84,43,67,73,80,83,69,78,68,61,48,44,52,13,10
“MESSAGE”	ASCII code of the “MESSAGE” characters

ASCII – American Standard Code for Information Interchange

module is configured as a server. At second, the serial port of the Raspberry Pi is activated for bidirectional data communication with the remote controller. After each data packet reception, header and footer bytes are checked and an acknowledgment packet is transmitted to the remote controller if the header and footer bytes are being correct. At the next step, the received data are processed to find out which operations are commanded. Finally, the commanded operations are executed by the GUI application while the serial port of the Raspberry-Pi is activated again to receive a new data packet. After receiving a new packet, the same procedure is repeated.

As mentioned in subsection II. A, some of the Raspberry-Pi’s GPIO pins are used in the proposed VAM system to control the external devices. However, GPIO pins cannot be controlled directly through an application coded in Visual Studio software. To overcome this shortcoming, the necessary GPIO control tasks are coded in Python IDE software and stored in several .py files. By doing so, to change the output state of a GPIO pin, its relevant .py file is executed through the proposed application by calling the System.Diagnostics.Process.Start() function, for example, System.Diagnostics.Process.Start(“task1.py”) to execute task1.py file.

In the proposed VAM system, the GUI application must be run automatically whenever the system is turned on. To do this, the following procedure is conducted to run the proposed GUI application at the startup time of the Raspberry-Pi operating system:

(i) The following two lines code is added to the last line of ‘/home/pi/.bashrc’ file:

```
echo Running at boot
sudo python/home/pi/file1.py
```

where, file1.py is a program intended to be run at startup;

(ii) Call the executable file of the proposed GUI application by adding the following code to the last line of file1.py:

```
from subprocess import call
```

```
Call(“/home/pi/Desktop/./VAM_App. exe”, shell = True)
```

where VAM_App. exe is the Linux-compatible version of the proposed GUI application;

(iii) reboot the Raspberry-Pi.

After conducting the above procedure, whenever Raspberry-Pi is turned on, the lcdapp. exe application is run automatically at the startup.

Remote controller program coded in C-language

The main task of the remote controller is to receive data packets from the HMI and transfer them to the Raspberry-Pi through the wireless network. To do this, USART1 serial port of the STM32 microcontroller is connected to the serial port of the HMI. Whenever a point is touched on the GLCD, four bytes with the following sequence are sent from the GLCD to the microcontroller:

```
<header_byte> <icon_ID> <page_number> <footer_byte>
```

The STM32 microcontroller receives these four bytes and transfers them to the Raspberry-Pi by sending necessary AT-commands to the ESP8266 module through the USART2 serial port. At the next step, the receiver interrupt of the USART2 unit is activated to receive the acknowledgment bytes from the Raspberry-Pi. If no acknowledgment is received, microcontroller sends previous four bytes again and waits for acknowledgment. Receiving no acknowledgment after two consecutive transmissions means that the wireless network is lost. Therefore, the microcontroller tries to reconnect to the Raspberry Pi’s ESP8266 module while at the same time, informs the user by loading a specified page [Figure 9] on the GLCD.

In the proposed VAM system, to keep the wireless communication alive, if no activity is detected on the network for more than 2 m, the microcontroller sends one data packet to the Raspberry-Pi and waits for acknowledgment. To do this, TIM1 unit of the microcontroller is configured such that an overflow interrupt occurs after identifying inactivity on the USART2 serial port of the microcontroller for two minutes. In the service routine of TIM1 interrupt, the wireless communication between the remote controller and Raspberry-Pi is checked.

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In order to monitor the voltage and state of charge of the lithium-polymer battery, TIM2 unit of the microcontroller is set such that overflow interrupts occur at each second. In the service routine function of TIM2 interrupt, the voltage of the battery is sampled by ADC unit of the microcontroller and then, the remaining charge of the battery is estimated according to the ADC conversion result and characteristic curve of the battery. If the remaining charge is below ten percent, a LED is turned on to inform the user and if the remaining charge is below 5%, the remote controller is turned off automatically to protect the battery against over-discharging.

Visual Acuity Testing Charts used in the Proposed Visual Acuity Measurement System

The following charts are stored in the proposed VAM system to provide wide options for visual acuity examinations:

Snellen E

This is the most common visual acuity testing chart that is widely used by the optometrist. The basic Snellen chart has eleven lines of letters array. The first line of the chart consists of one large letter while subsequent lines have increasing numbers of letters that decrease in size.

In the proposed VAM system, Snellen E chart can be displayed on the main LCD screen in a single letter format, horizontal array format, vertical array format, or square array format [Figure 10a].

The basic visual acuity examinations are conducted when the distance between the patient and the LCD screen is 6 meters (20 feet).^[14] In this condition, the smallest row that can be read accurately by the patient indicates his/her visual acuity. If the distance of the patient from the LCD is changed, size of the optotypes must be changed accordingly. Therefore, traditional visual acuity testing charts can only be used for a specific distance. To overcome this shortcoming, in the proposed VAM system, the size of the optotypes is adjusted automatically based on the distance of the patient from the LCD. To do this, the distance of the patient from the LCD is set through the remote controller and then, all of the optotypes are resized automatically by the proposed application running on the Raspberry-Pi.

Landolt C

Landolt C chart, also known as a Landolt ring chart, is another standardized chart in which, each optotype is a ring with a gap, thus looking similar to letter C. The gap can be placed at left, right, bottom, or top of the ring or in 45° positions between them. Similar to Snellen E chart, in the proposed VAM system, Landolt C chart can be displayed in a single letter format, horizontal array format, vertical array format, or square array format [Figure 10b]. Moreover, the size of the optotypes can be adjusted easily through the remote controller.

English number chart, English letter chart, and children chart

To provide more choices for visual acuity examinations, these charts are stored in the memory of the proposed VAM system. In the children's chart, simple pictures such as house, flower, and car are used as optotypes to simplify the visual acuity examinations for young children or people who cannot read.^[15] Similar to previous charts, in the proposed VAM system, these charts can be displayed in various formats [Figure 10c-e] while the size of their optotypes can be adjusted easily by setting the patient distance from the LCD.

Red/green and white/black background tests

To provide more options for visual acuity examinations, in the proposed VAM system, the background of the screen can be changed to a red/green page [Figure 11a] or a black page [Figure 11b]. These features help cataract patients to recognize optotypes easier.^[16]

Astigmatism tests

Astigmatism is a common vision defect that causes difficulties in near and far vision. In the proposed VAM system, various pictures are provided for examination of the patient's astigmatism. Some of these pictures are illustrated in Figure 12.

Color blindness tests

In the proposed VAM system, Ishihara test images as well as red/green colorblindness test images are provided for examination of the patients' colorblindness. Some of these images are presented in Figure 13.

Experimental Evaluation of the Proposed Visual Acuity Measurement System

Standard definition of normal visual acuity is the ability to resolve a spatial pattern separated by a visual angle of 1 min of arc.^[17]

The visual acuity of a patient can be examined as follows:^[17]

The optometrist asks the patient to remove his/her glasses or contact lenses and stand or sit at the specified location (often 20 feet) from the LCD. The patient must keep both his/her eyes open.

The optometrist asks the patient to cover one eye with the palm of his/her hand, or a piece of paper and then asks about the features of the different optotypes shown on the LCD. The patient must answer the questions based on what he/she can see on the LCD. The smallest line of optotypes that the patient can see on the LCD specifies his/her visual acuity.

The same procedure, mentioned above, must be conducted for each eye and one at a time. However, based on the optometrist's diagnosis, the examination can be repeated while the patient wears his/her glasses or contacts.

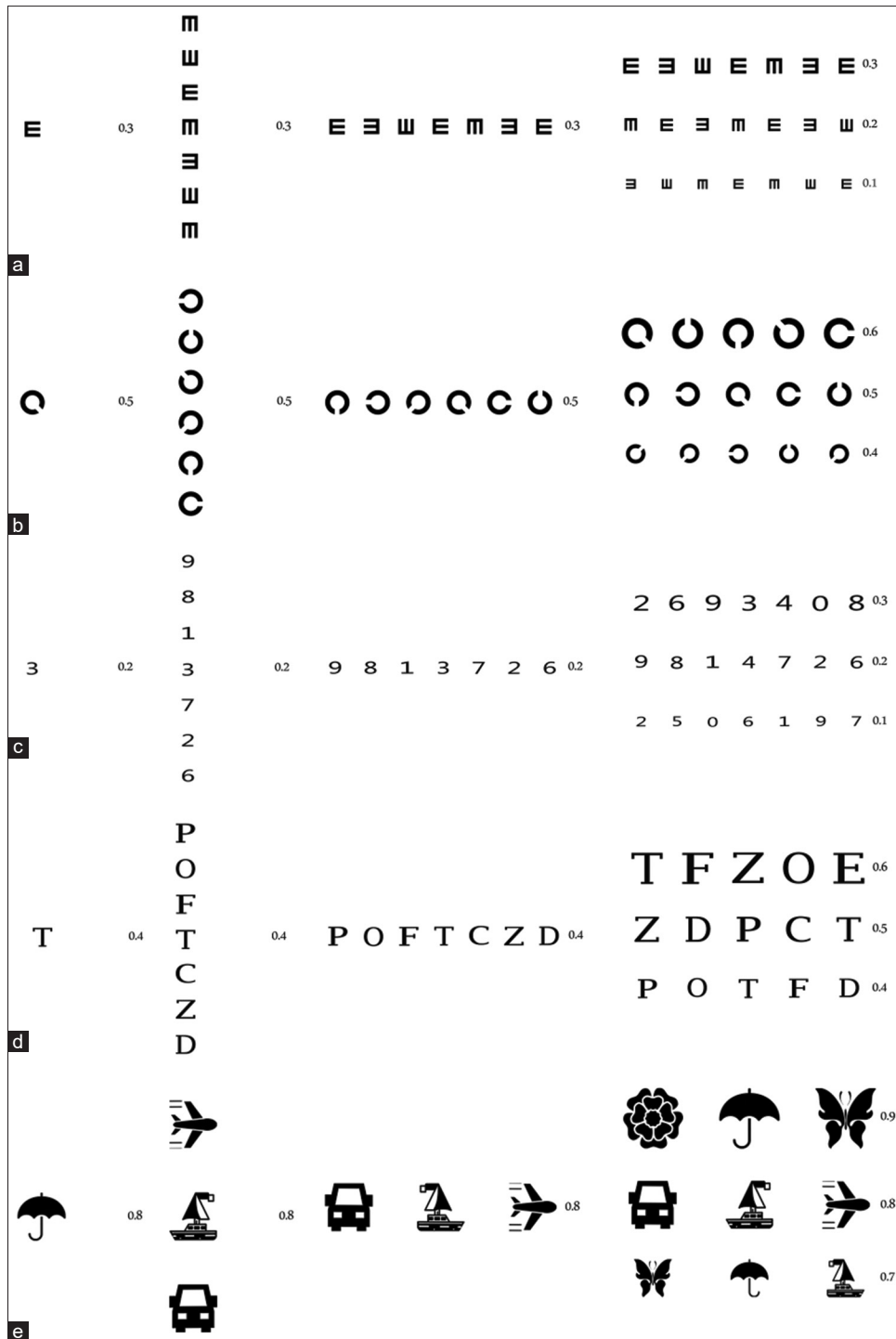


Figure 10: Examples of the optotypes stored in the proposed VAM system; (a) Snellen E, (b) Landolt C, (c) English number, (d) English letter, and (e) children chart characters. VAM: Visual acuity measurement

At the end of the examination, the optometrist expresses the visual acuity of the patient as a fraction where the top number refers to the distance the patient stand from the LCD and the bottom number indicates the distance at which a person with normal eyesight can read the same line that the patient reads correctly.

Visual acuity of 20/20 is considered the normal case while 20/40 indicates that the line the patient reads correctly from

distance of 20 feet can be read by a person with normal vision from distance of 40 feet.

Even if the patient misses one or two optotypes on the smallest line that he/she can see, he/she is still considered to have visual acuity equal to that line.^[18]

The procedure of examination of the patient’s visual acuity by the proposed VAM system is as follows:

At first, the distance between the patient and the LCD is specified by the optometrist, and then all of the optotypes are resized by the software accordingly. At the next step, based on the age, sex, and vision status of the patient, a proper chart is selected by the optometrist for examination. Then, various optotypes are shown on the LCD sequentially where the correctness of the patient's answers (True or False) is transmitted to the main controller by the optometrist through the remote controller. At the end of the experiment, based on the size of optotypes and the answers provided by the patient, the patient's visual acuity is calculated by the main controller and reported on the LCD.

In order to validate the performance of the proposed VAM system, the visual acuity of 45 adult patients with random

sex, age, and visual status in addition to the visual acuity of 30 children is measured in two manners:

- i. Patients are examined through SMART LC 13-LCD visual chart made by Medizs Inc. and their visual acuity values are calculated by an expert optometrist
- ii. Patients are examined through the proposed VAM system and their visual acuity values are calculated by the proposed VAM system automatically.

In these experiments, Snellen E and Landolt C charts are used for examination of the adult patients while English Number and Children Character charts are used for examination of the children.

The visual acuity values obtained by adopting the two manners, above, are presented in Table 4. As observed, the accuracy of the proposed VAM system is just similar to that of SMART LC 13-LCD visual chart for both the adult patients and the children groups.

It must be noted that:

- i. All of the experiments presented in this section for validation of the performance of the proposed VAM system are conducted according to^[17,18] which are international standards of VAM
- ii. Based on,^[18] visual acuity values are calculated by considering the following assumption: even if the patient misses one or two optotypes on the smallest line that he/she can see, the patient is still considered to have visual acuity equal to that line.

Conclusion

In this article, a smart VAM system is proposed. The hardware of the proposed VAM system consists of a

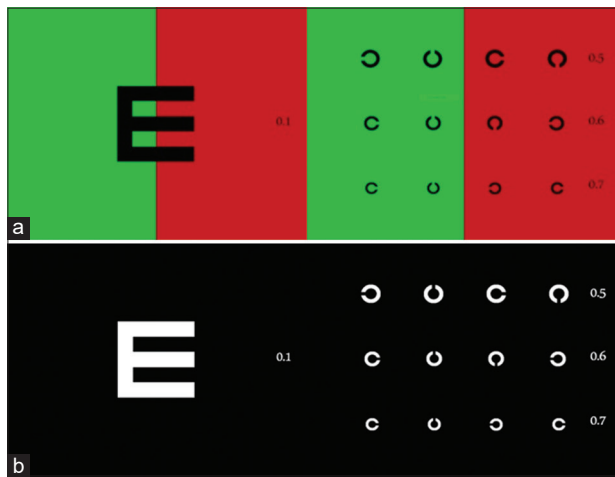


Figure 11: Optotypes with colored backgrounds: (a) red/green background, and (b) black background

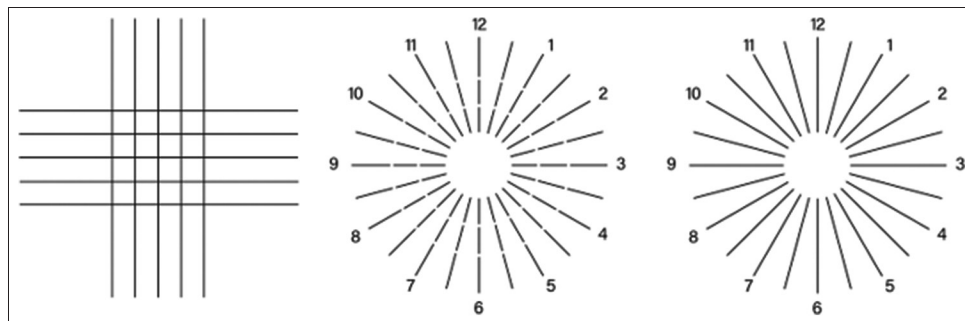


Figure 12: Some of the pictures used in examination of the patients' astigmatism

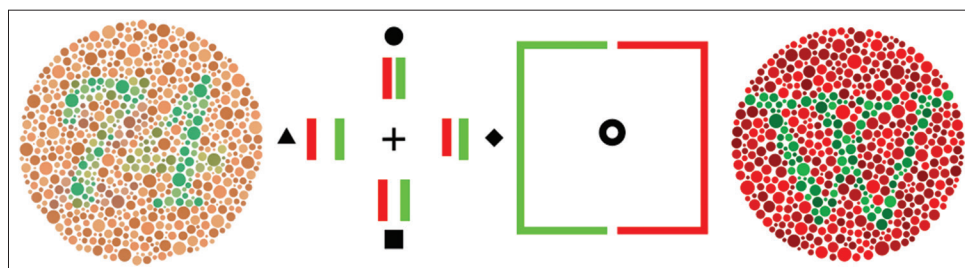


Figure 13: Some of the pictures used in examination of the patients' colorblindness

Table 4: Visual acuity values obtained by adopting the proposed visual acuity measurement system and the visual acuity measurement system made by Medizs Inc.

Patient	Obtained visual acuity value		Patient	Obtained visual acuity value		Patient	Obtained visual acuity value	
	Proposed VAM system	Medizs VAM system		Proposed VAM system	Medizs VAM system		Proposed VAM system	Medizs VAM system
Adult 1	20/160	20/160	Adult 16	20/20	20/20	Adult 31	20/120	20/120
Adult 2	20/20	20/20	Adult 17	20/20	20/20	Adult 32	20/80	20/80
Adult 3	20/20	20/20	Adult 18	20/40	20/40	Adult 33	20/20	20/20
Adult 4	20/20	20/20	Adult 19	20/60	20/60	Adult 34	20/40	20/40
Adult 5	20/100	20/100	Adult 20	20/30	20/30	Adult 35	20/30	20/30
Adult 6	20/40	20/40	Adult 21	20/30	20/30	Adult 36	20/60	20/60
Adult 7	20/20	20/20	Adult 22	20/25	20/25	Adult 37	20/50	20/50
Adult 8	20/20	20/20	Adult 23	20/20	20/20	Adult 38	20/25	20/25
Adult 9	20/80	20/80	Adult 24	20/20	20/20	Adult 39	20/20	20/20
Adult 10	20/20	20/20	Adult 25	20/20	20/20	Adult 40	20/20	20/20
Adult 11	20/30	20/30	Adult 26	20/20	20/20	Adult 41	20/20	20/20
Adult 12	20/25	20/25	Adult 27	20/100	20/100	Adult 42	20/100	20/100
Adult 13	20/30	20/30	Adult 28	20/80	20/80	Adult 43	20/80	20/80
Adult 14	20/60	20/60	Adult 29	20/30	20/30	Adult 44	20/25	20/25
Adult 15	20/100	20/100	Adult 30	20/20	20/20	Adult 45	20/20	20/20
Child 1	20/20	20/20	Child 11	20/20	20/20	Child 21	20/30	20/30
Child 2	20/20	20/20	Child 12	20/20	20/20	Child 22	20/20	20/20
Child 3	20/30	20/30	Child 13	20/20	20/20	Child 23	20/40	20/40
Child 4	20/25	20/25	Child 14	20/25	20/25	Child 24	20/20	20/20
Child 5	20/20	20/20	Child 15	20/25	20/25	Child 25	20/30	20/30
Child 6	20/40	20/40	Child 16	20/40	20/40	Child 26	20/20	20/20
Child 7	20/20	20/20	Child 17	20/40	20/40	Child 27	20/20	20/20
Child 8	20/20	20/20	Child 18	20/35	20/35	Child 28	20/20	20/20
Child 9	20/30	20/30	Child 19	20/20	20/20	Child 29	20/20	20/20
Child 10	20/25	20/25	Child 20	20/20	20/20	Child 30	20/20	20/20

VAM – Visual acuity measurement

remote controller and an LCD controller. An STM32 microcontroller is used in the remote controller to receive the user commands from a GLCD-based HMI and send them to the LCD controller. A Raspberry-Pi SBC is adopted in the LCD controller to receive the user commands from the remote controller and execute them through an application coded in Visual Studio software.

A wireless network implemented by two ESP8266 modules is used in the proposed VAM system for bidirectional data communication between the remote controller and the LCD controller.

Various optotypes are stored in the proposed VAM system to provide multiple choices for visual acuity examinations. Moreover, settings of the proposed VAM system as well as the necessary parameters of each examination can be adjusted easily through the remote controller.

The proposed VAM system is implemented and its performance is assessed experimentally under the supervision of an expert optometrist. Based on the experimental results and the optometrist’s opinion, the proposed VAM system has the following advantages:

i. Wireless network provides an easy and reliable solution to manage the content of the LCD screen. Moreover,

the wider operating range of the wireless network in comparison with the infrared-based remote controllers simplifies the usage of the device

ii. Touch screen GLCD used in the remote controller provides an easy and fast interface to communicate with the LCD controller and perform various visual acuity examinations

iii. Raspberry-Pi with its Linux-based operating system provides a fast and powerful environment to perform various visual acuity examinations, for example, size of the optotypes can be adjusted automatically, red/green or black background can be added to the optotypes, astigmatism examination can be conducted, etc

iv. Due to the huge storage space of the LCD controller, various charts, objects, and images in any desirable format can be stored in the proposed VAM system. Moreover, further charts, images, etc., can be added to the proposed VAM system through a USB flash memory.

Finally, based on the theoretical explanations provided in this article as well as the experimental tests, it can be deduced that the proposed VAM system is a good candidate for various visual acuity examinations.

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Conflicts of interest

There are no conflicts of interest.

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