A machine vision system applied to the teaching of mathematics for blind or visually impaired children

C. A. Calderon, Maria Guajala, John Lanchi, Luis Barba-Guaman, Carlos Bermeo, F. Rivas-Echeverría

Abstract—**This paper proposes the architecture and the procedure for the design and development of a new educational board game based on computer vision, which is an automated tutor oriented to special education institutions. For practical demonstration of the proposed system, we applied machine vision to educational board game focused on two-dimensional Braille math operations. Three tests were performed: 1) Test of performance of the machine vision based on cross-correlation algorithm, 2) Test of the algorithm that locates errors on the educational board game, and 3) Usability evaluation by visually impaired children and teachers at the Institute for Blind people Byron Eguiguren (Loja-Ecuador). As a result of 1), the average success rate is equal to 94.6%; as a result of 2), the algorithm locates 100% of possible errors; finally as a result of 3), aspects as interactivity, usability, likeability, and playability are met. These results indicate the high potential of the new application proposed of the machine vision systems; as a means for creating automated tutors applied to educational board games for visually impaired children, these teaching tools meet such characteristics as low-cost, fast and non-intrusive.**

Keywords—**machine vision, pattern matching, educational board game, visual impairment, blind, LabVIEW.**

I. Introduction

In Ecuador, according to the latest census population conducted in November 2010, there are 186.117 visually impaired people, and 17.081 is under 12 years old, so there are 1.2 visually impairment children (VIC) per 1000 inhabitants [1]. Nevertheless most special education institutions lack educational material aimed to VIC, on this basis in [2] it is proposed to generate educational material to enhance learning of mathematics in blind children, as a result of the project a wide set of educational board games applied to the main topics of basic education in mathematics was obtained, however these games need a teacher to monitor and feedback the operations performed by the VIC, this is a problem when these games are applied in classrooms of 10 or more VIC.

Referring to the problem identified, the scientific community has created some assistive technologies in the learning processes of visually impaired children (VIC).

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For example in [3] it is developed an Audio Video Describer using narration to visualize movie films; in [4] it is presented an embedded application (*Portáctil*) to aid the visually impaired that allows reading and writing printed or digitized documents; in [5] it is presented (*Braille Box*), an assistive device, developed by modifying Braille cells to form a tactile stimulator array which is compatible with the fingertip, this device allows people with impaired vision to access graphic information on computer screen by tactile perception; in [6] it is exposed the design, development and usability of two based on audio virtual environments (*AudioMath and Theo & Seth*) that increase mathematics learning in VIC.

On the other hand, they have generated technologies and tools for teachers in special education. For example in [7] it is enhancing a low-cost automated tutor designed to teach Braille writing skills to VIC using voice feedback. In [8] it is proposed a new pathway to interlink and translates inputs from keyboard into the most used Braille character automatically and enables normal visually people to have real time interaction with visually impaired person, and in [9] it is described a new system that recognizes Braille characters from image taken by a high speed camera to Chinese character and at the same time automatically mark the Braille paper, it should be emphasized that the core of the proposed system is image processing.

Based on the literature research, our contribution is the design and development of an automated tutor applied to educational board games for VIC, focused on math topics. The proposed system is a new application of machine vision, which allows automatically inspect the area of the game based on processing of the real-time acquired image, additionally, the feedback messages to the child are executed by voice signals.

To achieve the stated goal, first we analyzed the characteristics of the educational board game (section II). Then we defined the architecture of the machine vision and the procedure to be executed (section III), section IV describes each of the phases of defined procedure, in section V we present the experimental results at laboratory and usability testing at the Institute for Blind people Byron Eguiguren, finally, the main conclusions of the research project are summarized in section VI.

II. Description of educational board game

The educational board game (EBG) is a tool to teach mathematical operations to visually impaired children. The EBG consists of two elements, the game board and the set of 56 tabs. The size of the game board is 40 cm wide and 30 cm high, the size of gaming tabs is 4 cm wide and 5.5 cm high.

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With respect to the game board, the first row is a reference for the child, because it indicates the positions of the units, tens, hundreds, thousands and the number sign. The second and third row, have the boxes to enter the first and the second number up to 4 digits, also in the third row it is the box to enter the symbol of the mathematical operation to be performed. Finally, the fourth row consists of the boxes to enter the result of the operation between the numbers entered; this result can be up to 5 digits.

With respect to gaming tabs, each have their respective symbol (1, 2, 3, 4, 5, 6, 7, 8, 9, 0, +, -, x, #) supplemented with the corresponding Braille code and a distinctive color, this last feature is helpful for children who have partial visual impairment. The Braille code developed embossed is used to identify the symbol by touch [2]. Fig. 1 shows the elements of the educational board game, and Fig. 2 shows an example of using the board and tabs of the educational board game focused on two-dimensional Braille math operations.

In this educational board game, is necessary a teacher who monitors and feedbacks the activities of the VIC, such as the child wants to know if entered correctly the numbers, or also the child needs to identify whether the entered result is correct or incorrect. Knowing this type of educational games is applicable to special educational institutions; potential problems are foreseen if these games are used in classrooms of 10 or more VIC.

Based on the above, we propose to design and implement an automated tutor based on machine vision, applied to educational board games for VIC, focused on math topics of basic education.

III. Machine vision: architecture

The machine vision is composed of: a computer used as a central processing element and three peripheral devices: digital camera, speakers, and a keypad (Fig. 3). The central computer runs the software to monitor the educational board game; to this software we named it *Axes*, It is developed in LabVIEW 2014 programming language from National Instruments, and it uses the functions of Vision Development Module (VDM) which is a library of commands to develop image processing applications. The LabVIEW and VDM software is widely used for the development of machine vision systems, for example in [10]-[13].

The peripheral devices that are part of the proposed system are: camera, speakers and keypad. Regarding the function of this devices; the Genius FaceCam 1020 commercial camera captures the image in real time with a maximum acquisition rate of 30 fps (frames per second) with a resolution of 1280x720 pixels. The speakers are the sound interface device from the computer to the VIC, by means of this device the computer communicates to the child about the state of educational game, by playing error and information messages which are generated automatically by the *Axes* software. Finally, the keypad is the touch interface between the VIC and the computer, it has four buttons marked with the letters *a*, *b*, *c*, and *d*; the function of the *a* and *b* buttons is to recognize the first and the second number respectively; *c* button function is to recognize the mathematical operation and check the result entered; and *d* button function is to recognize and check all numbers entered on the game board.

The preliminary conceptualization of this system applied to the need identified, is shown in [14]-[15], the method for generating ideas, selecting ideas and creating these prototypes, is based on the Game Jam model [16].

IV. Machine vision: procedure

The *Axes* processing software executes a sequence of steps, from the acquisition of the image in real-time until to check the EBG result. The procedure (Fig. 4) which performs *Axes*, is outlined in detail below:

- Read the image acquisition device.
- Segment the image of the game board.
- Extract and learn the symbolic patterns of the tabs.
- Determine regions of belonging to the boxes.
- Identify the symbolic patterns.
- Determine the symbolic matrix.
- Locate errors and check the result.

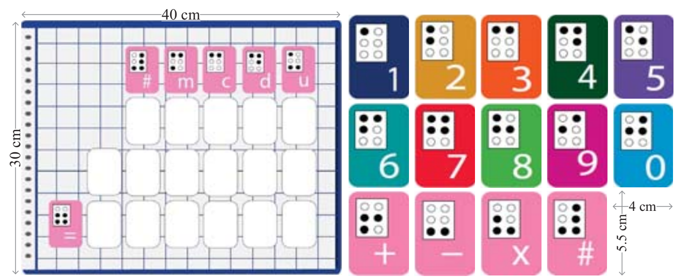

Fig. 1. Elements of the educational board game.

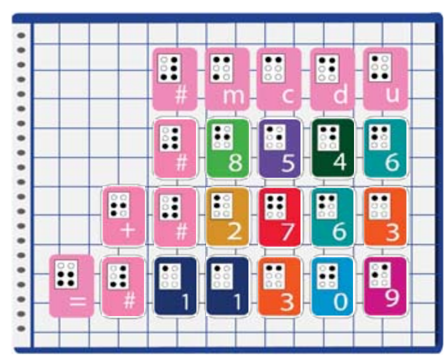

Fig. 2. Example of using the board and tabs of the educational board game focused on math operations.

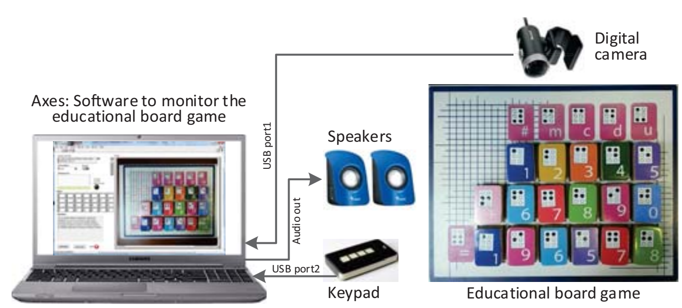

Fig. 3. Machine vision architecture applied to educational board game.

A. *Read the image acquisition device*

To read the image from acquisition device, the supplement called IMAQdx driver software was used, which is compatible with LabVIEW and allows integrating digital video cameras to acquire images. The steps to acquire the image in real-time are: initialization, configuration and acquisition.

Initialization involves opening a session of the camera, for this the parameters are specified: camera name and control mode; the label of our test camera is *cam1* and the control mode used is *listener*. The configuration we specified is: acquisition mode set to *continuous* and number of internal buffers equal to *3*. For the acquisition step, two user buffers were created: one for RGB images (U32) and one for Grayscale images (U8); U32 and U8 symbolizes the numeric data type used to represent each pixel; these data types are Unsigned 32-bit and Unsigned 8-bit, respectively. The output of acquisition step is the sequence of images acquired in real-time.

B. *Segment the image of the game board*

After acquiring the image of the game board, the segmentation process get started. This step is to identify the edge of the game board and proceed to divide the image into 28 cells (4 rows, 7 columns) in order that these cells correspond to actual boxes of the board game. To perform segmentation, they performed the following steps: First, it automatically determines the limits of the board game X_0, X_7, Y_0, and Y_4, then based on (1) the boundaries X_i and Y_j of each cell are calculated; the region of interest (ROI) of each cell $\boldsymbol{ROI\_C_{j,i}}$ is defined by (2). In Fig. 5 the matrix distribution of the cells $\boldsymbol{C_{j,i}}$ on the acquired image is displayed.

$$\alpha = \frac{X_7 - X_0}{7}, \quad \beta = \frac{Y_4 - Y_0}{4}$$

$$X_i = X_0 + i\alpha, \qquad i = 0 \ldots 7 \tag{1}$$

$$Y_j = Y_0 + j\beta, \qquad j = 0 \ldots 4$$

$$ROI\_C_{j,i} = [X_i, Y_i, X_{i+1}, Y_{j+1}] \tag{2}$$

Based on the geometry of the gaming tabs, they identify three ROIs; the Braille code region, the symbolic character region, and the color region (Fig. 6). In this step, we defined that the central element for learning and pattern recognition is the symbolic character. Therefore, as a next step the boundaries of the ROIs of the symbolic characters are determined ($\boldsymbol{ROI\_Nm_{j,i}}$), in order to extract reference images and then send them to the learning routine of the symbolic patterns. $\boldsymbol{ROI\_Nm_{j,i}}$ boundaries are described by a vector whose elements are: coordinate *(x,y)* lower and coordinate *(x,y)* upper. Based on Fig. 2, the cells containing tabs, they are those highlighted in gray color in Fig. 5. To the cell $C_{1,2}$ to $C_{1,6}$ the ROI boundaries are calculated using (3) for the cell $C_{2,1}$ to $C_{2,6}$ boundaries are calculated using (4) and for the cell $C_{3,1}$ to $C_{3,6}$ boundaries are calculated using (5).

$$ROI\_Nm_{1,i} = [X_i + \frac{\alpha}{2}, Y_1 + \frac{\beta}{2}, X_i + \alpha, Y_1 + \beta] \tag{3}$$

$$ROI\_Nm_{2,i} = [X_i + \frac{\alpha}{2}, Y_2 + \frac{\beta}{2}, X_i + \alpha, Y_2 + \beta] \tag{4}$$

$$ROI\_Nm_{3,i} = [X_i + \frac{\alpha}{2}, Y_3 + \frac{\beta}{2}, X_i + \alpha, Y_3 + \beta] \tag{5}$$

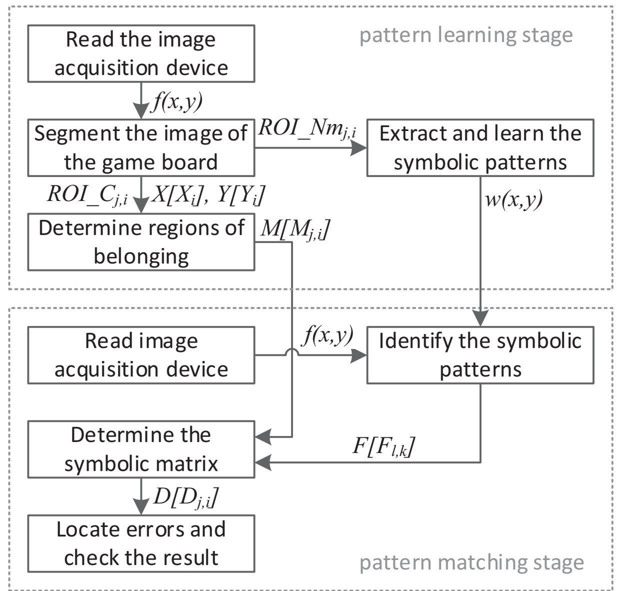

Fig. 4. Procedure Flowchart performed in the Axes processing software.

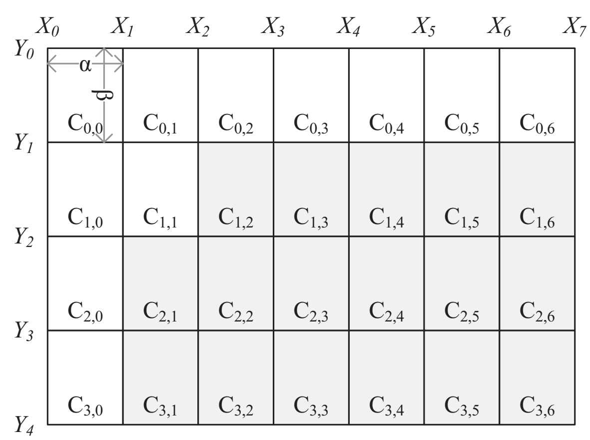

Fig. 5. Matrix distribution of the cells Cj,i on the acquired image.

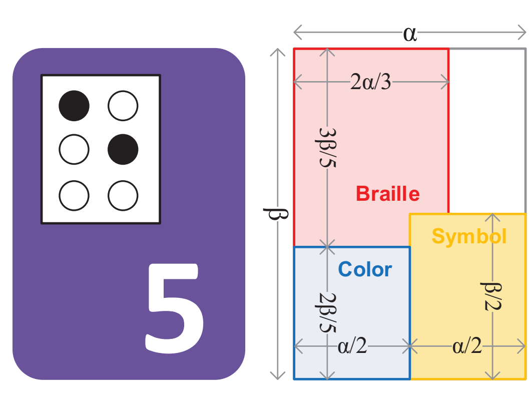

Fig. 6. Geometry of the Regions of Interest in the gaming tabs.

C. Extract and learn the symbolic patterns

Regions of interest $\boldsymbol{ROI\_Nm_{j,i}}$ determined in the previous step, allow extract from the source image *f(x,y)*, the reference images corresponding to the fourteen symbols of the gaming tabs. This reference images are called template images *w(x,y)*, which are sent to the routine of learning patterns of the Vision Development Module for LabVIEW. Fig. 7 shows the relation between the source image and template images.

D. Determine regions of belonging to the boxes

Regions of belonging are used to assign each identified pattern to the corresponding cells $C_{j,i}$ of Fig. 5. These regions of belonging are delimited by a circle centered at each midpoint $M_{j,i}$ with a radius equal to β/2; all these points form the $\boldsymbol{M}$ matrix; the midpoints $M_{j,i}$ are calculated using (6).

$$M = \begin{bmatrix} M_{0,0} & M_{0,1} & M_{0,2} & M_{0,3} & M_{0,4} & M_{0,5} & M_{0,6} \\ M_{1,0} & M_{1,1} & M_{1,2} & M_{1,3} & M_{1,4} & M_{1,5} & M_{1,6} \\ M_{2,0} & M_{2,1} & M_{2,2} & M_{2,3} & M_{2,4} & M_{2,5} & M_{2,6} \\ M_{3,0} & M_{3,1} & M_{3,2} & M_{3,3} & M_{3,4} & M_{3,5} & M_{3,6} \end{bmatrix}$$

$$M_{1,i} = [X_i + \frac{\alpha}{2}, Y_1 + \frac{\beta}{2}], \qquad i = 2...6 \tag{6}$$

$$M_{2,i} = [X_i + \frac{\alpha}{2}, Y_2 + \frac{\beta}{2}], \qquad i = 1...6$$

$$M_{3,i} = [X_i + \frac{\alpha}{2}, Y_3 + \frac{\beta}{2}], \qquad i = 1...6$$

E. Identify the symbolic patterns

In this step, the pattern matching algorithm based on cross-correlation method is executed, the cross correlation between each image template *w(x,y)* and the whole image *f(x,y)* of the educational board game at a point *(i,j)* can be mathematically determined by (7), [17]-[19].

$$CC(i,j) = \sum_{y=0}^{L-1}\sum_{x=0}^{K-1} w(x,y) f(x+i, y+j) \tag{7}$$

Where *w(x,y)* contains K x L pixels and *f(x,y)* contains M x N pixels with $K \le M$ and $L \le N$, i and j are varied from 0 to M-1 and from 0 to N-1, respectively. Based on the equation, the highest possible CC value is obtained when *f(x,y)* is exactly the same as *w(x,y)*, on the other hand, when *f(x,y)* is totally unmatched to *w(x,y)*, a cross correlation value of 0 is determined.

Search parameters are as follows: Minimum match score equal to 0.76; this is the minimum value of the NCC index (Normalized Cross Correlation) which means that the source image and the template image are the same, the NCC index range is from 0 to 1 for 0% and 100% similarity, respectively. Maximum number of matches requested equal to 4; based on this value follows that the maximum size of the $\boldsymbol{F}$ matrix is 14x4.

The result of this step is the $\boldsymbol{F}$ matrix, it is specified in (8); that it is formed by the positions and type of the identified elements. For example the first row is formed of the positions of the found tabs, which containing the 1 symbol, the second row is formed of the positions of the found tabs, which containing the 2 symbol, and so on until the fourteenth row that is formed of the positions of the found tabs, which containing the # symbol.

$$F = \begin{bmatrix} F_{0,0} & F_{0,1} & F_{0,2} & F_{0,3} \\ F_{1,0} & F_{1,1} & F_{1,2} & F_{1,3} \\ ... & ... & ... & ... \\ F_{12,0} & F_{12,1} & F_{12,2} & F_{12,3} \\ F_{13,0} & F_{13,1} & F_{13,2} & F_{13,3} \end{bmatrix} \tag{8}$$

F. Determine the symbolic matrix

To determine the $D_{j,i}$ elements of the $\boldsymbol{D}$ symbolic matrix, it proceeds to relate the $F_{l,k}$ elements of the $\boldsymbol{F}$ matrix with the $M_{j,i}$ elements of the $\boldsymbol{M}$ matrix and its regions of belonging associated; the nominal size of the D matrix is 3x6. The comparison function is expressed in (9).

$$F = \begin{bmatrix} D_{0,0} & D_{0,1} & D_{0,2} & D_{0,3} & D_{0,4} & D_{0,5} \\ D_{1,0} & D_{1,1} & D_{1,2} & D_{1,3} & D_{1,4} & D_{1,5} \\ D_{2,0} & D_{2,1} & D_{2,2} & D_{2,3} & D_{2,4} & D_{2,5} \end{bmatrix}$$

$$if\left(\overrightarrow{F_{l,k} M_{j,i}} \le \frac{\beta}{2}\right), \quad then \tag{9}$$

$$F_{l,k} \in C_{j,i} \therefore D_{j,i} = symbol\_of\_F_{l,k}$$

G. Locate errors and check the result

In this step, the machine vision locates existing errors in the arrangement of the tabs on the game board. First we extract each of the rows corresponding to the three numbers entered, then syntax errors for each number are identified, after the numerical value of each row is calculated (10), and finally, the mathematical operation result is checked.

$$Nm\_k = \sum_{i=0}^{3} 10^i C_{k,(6-i)} \tag{10}$$

The output of this step is the set of error messages; which are then played so that the VIC heard through the speakers connected to the computer; to play audio we used the library of Microsoft Speech SDK for TTS (text to speech) applications. The set of error messages is shown in Table I.

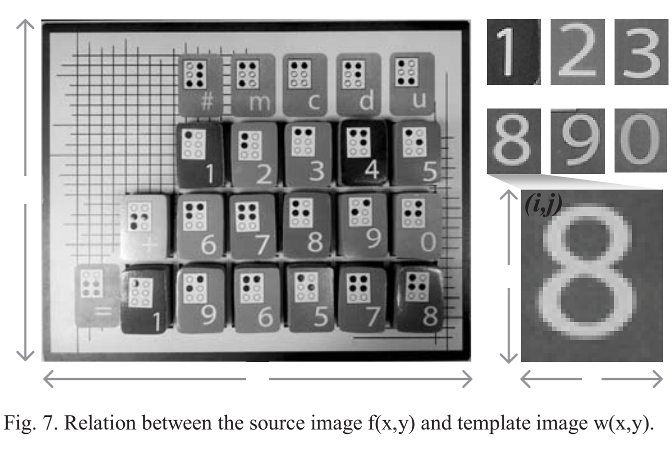

Fig. 7. Relation between the source image f(x,y) and template image w(x,y).

TABLE I
SET OF MESSAGES WHICH ARE PLAYED BY THE SOFTWARE

Label	Description
Err1	The first number does not have the # symbol.
Err2	The first number contains incorrect symbols.
Err3	The second number does not have the # symbol.
Err4	The second number contains incorrect symbols.
Err5	The result number does not have the # symbol.
Err6	The result number contains incorrect symbols.
Err7	The mathematical operation is not defined.
Err8	The result entered is incorrect. The correct result is *abcd*.
Mess1	You entered the first number: *abcd*. You entered the second number: *efgh*. You entered the result number: *xyzw*. Therefore, the solution is correct.

V. EXPERIMENTAL RESULTS

The prototype implemented is shown in Fig. 8. Boxes 1 and 2 show the educational board game and the set of tabs; box 3 shows the commercial camera Genius FaceCam 1020 with video resolution of 720P HD in 1280x720 pixels, up to 30 fps; box 4 shows the computer used for performing the procedure of machine vision, the model we used is Hewlett Packard Pavilion 14 Core i7 4702MQ /2.2 GHz with Windows 8/64 bits; finally, box 5 shows the front panel of the *Axes* software. This prototype was used for laboratory and field tests.

Three tests were performed: 1) Test of performance of the machine vision based on cross-correlation algorithm, 2) Test of the algorithm that locates errors on the educational board game, and 3) Usability evaluation by visually impaired children.

Tests of performance of the machine vision we conducted it in the laboratory. We performed 25 experiments for the 14 tab types; for different positions and quantities; the experiments were distributed as follows: Ten experiments were performed with the game board horizontally oriented with respect to the camera (*Ehor*). Five experiments were performed with the game board with an inclination angle of from 5° to 15° in the direction of clockwise (*Ecw*). Five experiments were performed with the game board with an inclination angle from 5° to 15° counterclockwise to clockwise (*Eccw*). Finally five experiments with the variable distance between the game board and the camera (*Edvar*); variation of distance is from 45 cm to 55 cm. The success rates (*Sr*) in the experiments are shown in Fig. 9. The procedure which performs the *Axes* software it takes about 400 milliseconds.

Then we performed the test of the algorithm that locates errors on the educational board game, Fig. 10 shows the results of the ***D*** matrix and of the error messages for some specific cases of the game board.

Finally we conduct usability testing by children and teachers visually impaired. The prototype tests were performed by 2 teachers and 3 children (8, 11 and 13) all were total visually impaired; they all belong to the Institute for Blind people Byron Eguiguren (IBBE).

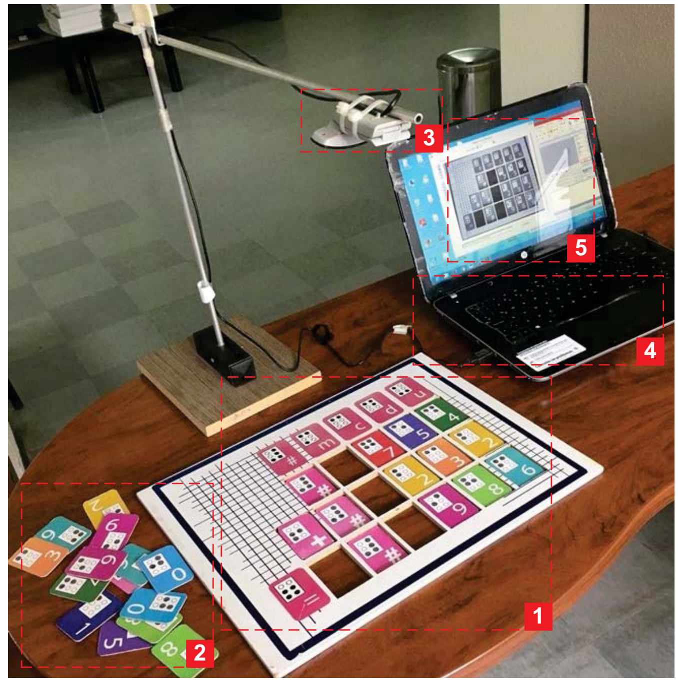

Fig. 8. Experimental setup for machine vision system.

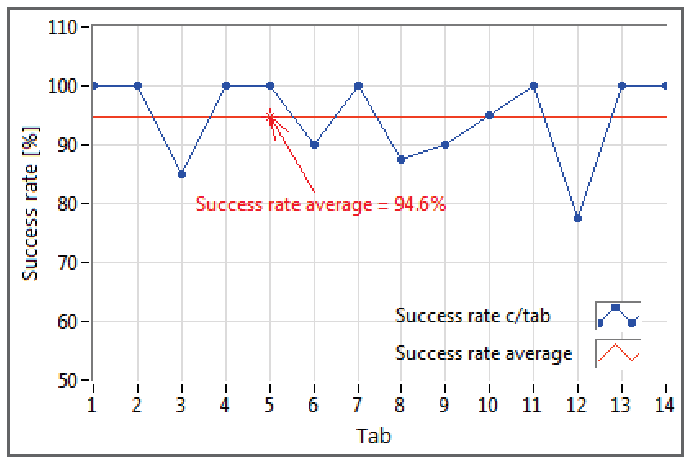

Fig. 9. Success rate average for each gaming tab.

The IBBE is located in the city of Loja (Ecuador), this has 21 students: 10 are total visually impairment, and 11 are partial visually impairment. However, it was not possible that all students test the prototype because not all have a mastery of Braille code; we obtained the following inferences:

- The children were quickly captured by the educational board game, due to its interactivity through sound messages based on voice.
- The Braille code of the gaming tabs does not have the standard size; however this was not a problem to use the educational board game.
- According to teachers of the IBBE, the prototype is a useful tool to: improve motor skills, increase logical reasoning, training in Braille numbers and mathematical operations. It is noteworthy that these topics are the most complicated, therefore the teachers recommend to take the prototype for internal use at the Institute.

Fig. 9. Results of the *D* Matrix and of the Error Messages for some specific cases of the game board. This figure shows the numerical matrix D correctly extracted from the acquired image in real time, also shows the correct identification of the specific cases Err1, Err3, Err5 and Mess1.

- Based on the proposals contained in [20] and [21]; aspects to consider in testing educational games are: interactivity, usability, likeability, and playability. Based on oral survey, these four aspects are met by the proposed system; however, it needs to propose and apply a specific methodology for testing such systems.
- The main elements of the proposed system are: voice guidance and Braille code in gaming chips; because the primary senses that visually impaired people use to learn are: hearing and touching.

VI. Conclusions

An automated tutor applied to educational board games (focused on math topics) for visually impaired children was designed and developed. Experimental tests of the architecture and the procedure proposed, is demonstrated by applying of the system to the educational board game for two-dimensional Braille mathematical operations. The proposed system is a new application of machine vision; it consists of a computer used as a central processing element and three peripheral devices: digital camera, speakers, and a keypad.

Three tests were performed: 1) Test of performance of the machine vision based on cross-correlation algorithm, 2) Test of the algorithm that locates errors on the educational board game, and 3) Usability evaluation by visually impaired children and teachers at the Institute for Blind people Byron Eguiguren. As a result of 1), the average success rate for the *Ehor*, *Ecw*, *Eccw*, and *Edvar* experiments; is equal to 94.6%. As a result of 2), the algorithm locates 100% of possible errors. Finally as a result of 3), based on oral survey; aspects as interactivity, usability, likeability, and playability are met. These results indicate the high potential of the new application proposed of the vision machines; as a means for creating automated tutors applied to educational board games for visually impaired children.

As future work we propose the implementation of the machine vision algorithms in a portable device based on DSP and FPGA, for example the electronic module used in [22].

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