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Recognition of American Sign Language Fingerspelling by Applying Matrix Matching Algorithm Using Leap Motion Controller Sensor

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Abstract: This paper presents the recognition of American Sign Language Fingerspelling by applying Matrix Matching algorithm using Leap Motion Controller Sensor. The study focused on the recognition of all the static and dynamic letters to increase the recognition rate and avoid misclassification. With proper hand orientation of the user and using the Leap Motion Controller Sensor's skeletal tracking feature, the researchers were able to acquire the joint coordinates of the distal and proximal phalanges of the human hand. These acquired joint coordinates were then used to create two matrices where matrix multiplication was then applied to generate a unique output matrix. Reduction of row elements as well as the column elements were used by the researchers to derive the Horizontal and Vertical resultant matrices to uniquely represent the letters in American Sign Language Fingerspelling. The letters would then be recognized by the system once the generated resultant matrix matched the reference resultant matrix in the system program. The process of matrix subtraction was executed in the matching process of the algorithm.
Keywords*: *American Sign Language Fingerspelling, Leap Motion Controller sensor, Matrix Matching Algorithm, Horizontal Resultant Matrix, Vertical Resultant Matrix

I. INTRODUCTION

American Sign Language is the predominant sign language exploited by deaf individuals in the United States and some part of Canada. It is also widely used in many countries around the world including West Africa and parts of Southeast Asia. The Deaf Community utilizes American Sign Language through the use of gestures as a medium in communicating with other people. Fingerspelling, as part of American Sign Language, is a system where each letter of the English alphabet is represented by a unique hand gesture. Fingerspelling is an important part of the language, in which signers spell out a word as a sequence of hand shapes corresponding to individual letters.

Many researches and studies regarding American Sign Language and Hand Gesture recognition have been made and developed [2][3]. The study Hand Gesture Recognition with Leap Motion and Kinect Devices proposed a novel hand gesture recognition scheme explicitly targeted to Leap Motion data. An ad-hoc feature set based on the positions and orientation of the fingertips is computed and fed into a multi-class Support Vector Machine (SVM) classifier in order to recognize the performed gestures. A set of features is also extracted from the depth computed from the Kinect and combined with the Leap Motion in order to improve the recognition performance. There are some of the gestures that frequently fail in the recognition, because these gestures were still critical for the Leap Motion from the combined feature set used in the study [4].

A recent study entitled American Sign Language Recognition Using Leap Motion Sensor uses two algorithms, the k-Nearest Neighbor and Support Vector Machine for the recognition of the letters. But the recognition on some of the signs were still inaccurate, which causes for some of the letters to be misclassified by the system. The experiment result of the study shows that the highest average classification rates of 72.78% and 79.83% were achieved by *k*-Nearest Neighbor and Support Vector Machine respectively. Due to this inaccuracy rate, some of the letters are being mislabeled. Generally, the misclassification can be explained by the similarity of the hand shapes between the letters [1].

To solve this problem, the use of Matrix Matching Algorithm is proposed by the researchers to be able to recognize the letters of American Sign Language Fingerspelling. The system design uses matrices derived from the finger joints of the hand. Hence, a more

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unique and distinct data will be generated to solve the misclassification of the letters of American Sign Language Fingerspelling. The whole study focused on the American Sign Language Fingerspelling developing a system that would help the deaf people to communicate with other people. The study also aimed to highlight how the concept of matrices helps in the recognition of letters in American Sign Language and prevent misclassification in the system recognition.

II. METHODOLOGY

As the user provides a fingerspelling hand gesture positioning his hand above the Leap Motion controller sensor within its interaction area, the controller then operates identifying the position of the hand and palm center, orientation of each finger bone, and provides the vector coordinates of the user's finger joints. After then, through the Leap Motion controller sensor, the system acquires the distal and proximal phalangeal joint coordinates of the human hand that is being tracked. The researchers used the acquired joint coordinates forming two distinct matrices. The process of Matrix Multiplication was then applied between the generated matrices for distal and proximal phalangeal joints generating an output matrix. Through reduction of row elements and reduction of column elements, Horizontal Resultant Matrix and Vertical Resultant Matrix were then formed. The application of *Matrix Matching Algorithm* was then used in the recognition of the letters in American Sign Language Fingerspelling. The process of matrix subtraction was executed in the matching process of the algorithm.

A. Determining the Resultant Matrix

Acquisition of Distal and Proximal Phalangeal Joint Coordinates of the Human Hand: The researchers used the Leap Motion controller sensor's skeletal tracking feature that focuses on tracking human's fingers to obtain the 3D skeletal joint coordinates. The researchers integrated the Software Development Kit (SDK) skeletal tracking feature of the sensor with Visual Studio software, and created a C# code to acquire the values of the joint coordinates of the human hand. The palm center of the human hand was being set as the *origin.*

Fig. 1 Distal and proximal phalangeal joints of the human hand

The researchers selected the five distal and five proximal phalanges to acquire the distal and proximal phalangeal joint coordinates of the human hand with respect to the palm center as the origin. These were selected since these two phalanges generally best represent the handshape of the fingerspelling hand-gesture in order to establish a distinct feature.

1) *Forming Matrices and Applying Matrix Multiplication:* The researchers used the concept of matrix to represent the distal and proximal joint coordinates. Hence, generating two matrices: a matrix for the distal phalangeal joint coordinates (distal matrix or *Matrix D*) and another matrix for the proximal phalangeal joint coordinates (proximal matrix or *Matrix P*).

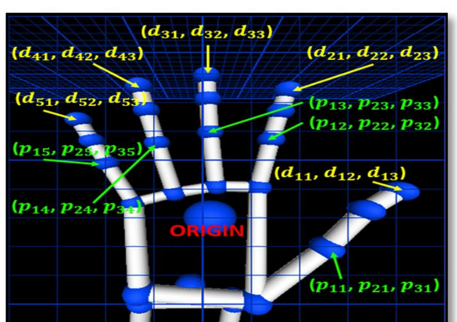

Fig. 2 Coordinates of the distal and proximal phalangeal joints of the tracked human hand using the skeletal tracking of theLeapMotion controller sensor

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$$\mathbf{D} = \begin{array}{c} \begin{array}{ccc} x_d & y_d & z_d \end{array} \\ \begin{bmatrix} d_{11} & d_{12} & d_{13} \\ d_{21} & d_{22} & d_{23} \\ d_{31} & d_{32} & d_{33} \\ d_{41} & d_{42} & d_{43} \\ d_{51} & d_{52} & d_{53} \end{bmatrix} \end{array} \begin{array}{c} \\ \text{thumb} \\ \text{index} \\ \text{middle} \\ \text{ring} \\ \text{little} \end{array} \quad (1)$$

$$\mathbf{P} = \begin{array}{c} \begin{array}{ccccc} \text{thumb} & \text{index} & \text{middle} & \text{ring} & \text{little} \end{array} \\ \begin{bmatrix} p_{11} & p_{12} & p_{13} & p_{14} & p_{15} \\ p_{21} & p_{22} & p_{23} & p_{24} & p_{25} \\ p_{31} & p_{32} & p_{33} & p_{34} & p_{35} \end{bmatrix} \end{array} \begin{array}{c} \\ x_p \\ y_p \\ z_p \end{array} \quad (2)$$

After the distal and proximal matrices were formed, the researchers then used the concept of *matrix multiplication* from Advanced Engineering Mathematics to derive a single matrix that would represent the letter in American Sign Language Fingerspelling.
Let the distal and proximal matrix be represented by the expressions $\boldsymbol{D} = \boldsymbol{a} \ \boldsymbol{x} \ \boldsymbol{b}$ and $\boldsymbol{P} = \boldsymbol{c} \ \boldsymbol{x} \ \boldsymbol{d}$ respectively. The output matrix then would have the size of $\boldsymbol{a}$ (row of distal Matrix D) by $\boldsymbol{d}$ (column of proximal Matrix P). The process is explained by the equations below, that is:

$$\mathbf{O} = \mathbf{D} \ \boldsymbol{x} \ \mathbf{P} \quad (3)$$

$$\mathbf{O} = [\, \mathbf{a} \ x \ \mathbf{b} \,] x \, [\mathbf{c} \ x \ \mathbf{d} \,] \quad (4)$$

$$if \ b = c,$$

$$then, \ \mathbf{O} = [\, \mathbf{a} \ \boldsymbol{x} \ \mathbf{d} \,] \quad (5)$$

Solving for the output matrix **O,** we have:

$$\mathbf{O} = \begin{bmatrix} d_{11} & d_{12} & d_{13} \\ d_{21} & d_{22} & d_{23} \\ d_{31} & d_{32} & d_{33} \\ d_{41} & d_{42} & d_{43} \\ d_{51} & d_{52} & d_{53} \end{bmatrix} x \begin{bmatrix} p_{11} & p_{12} & p_{13} & p_{14} & p_{15} \\ p_{21} & p_{22} & p_{23} & p_{24} & p_{25} \\ p_{31} & p_{32} & p_{33} & p_{34} & p_{35} \end{bmatrix} \quad (6)$$

Hence, the output matrix then will be a five by five matrix **O = [5 *x* 5]** and is considered to be a square matrix.
For the simplicity of the analysis, we let the elements of the output matrix be represented defined as:

$$\mathbf{O} = \begin{bmatrix} m_{11} & m_{12} & m_{13} & m_{14} & m_{15} \\ m_{21} & m_{22} & m_{23} & m_{24} & m_{25} \\ m_{31} & m_{32} & m_{33} & m_{34} & m_{35} \\ m_{41} & m_{42} & m_{43} & m_{44} & m_{45} \\ m_{51} & m_{52} & m_{53} & m_{54} & m_{55} \end{bmatrix} \quad (7)$$

2) *Obtaining Horizontal and Vertical Resultant Matrices*: Reduction of row elements is then next. The researchers determined the minimum and maximum element values for each of the five rows in the output matrix. Each minimum element value was then subtracted to the five elements of that specific row to which the minimum element value corresponded.

For instance *(case for letter A),* we let the minimum element values be represented by the column vector $\boldsymbol{r_{min}}$, that is:

$$\boldsymbol{r_{min}} = \begin{bmatrix} m_{15} \\ m_{25} \\ m_{35} \\ m_{41} \\ m_{51} \end{bmatrix} \quad (8)$$

The new resulting matrix **R** was derived as:

$$\mathbf{R} = \mathbf{O} - \boldsymbol{r_{min}} \quad (9)$$

$$\mathbf{R} = \begin{bmatrix} m_{11} & m_{12} & m_{13} & m_{14} & m_{15} \\ m_{21} & m_{22} & m_{23} & m_{24} & m_{25} \\ m_{31} & m_{32} & m_{33} & m_{34} & m_{35} \\ m_{41} & m_{42} & m_{43} & m_{44} & m_{45} \\ m_{51} & m_{52} & m_{53} & m_{54} & m_{55} \end{bmatrix} - \begin{bmatrix} m_{15} \\ m_{25} \\ m_{35} \\ m_{41} \\ m_{51} \end{bmatrix} \quad (10)$$

()

Also, we let the maximum element values be represented by the column vector $\boldsymbol{r_{max}}$, that is:

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$$\boldsymbol{r_{max}} = \begin{bmatrix} m_{11} - m_{15} \\ m_{21} - m_{25} \\ m_{31} - m_{35} \\ m_{43} - m_{41} \\ m_{55} - m_{51} \end{bmatrix} \tag{11}$$

The column vector $\boldsymbol{r_{max}}$ was then divided from the obtained matrix **R**, corresponding to the five elements of that specific row to which the maximum element value corresponded. Consequently, all the other numerical matrix elements aside from *0 and 1* were assigned as *2*. The resultant matrix $\mathbf{R_H}$ (Horizontal matrix) was then derived as follows:

$$\mathbf{R_H} = \mathbf{R} / \boldsymbol{r_{max}} \tag{12}$$

$$\mathbf{R_H} = \begin{bmatrix} \frac{m_{11}-m_{15}}{m_{11}-m_{15}} & \frac{m_{12}-m_{15}}{m_{11}-m_{15}} & \frac{m_{13}-m_{15}}{m_{11}-m_{15}} & \frac{m_{14}-m_{15}}{m_{11}-m_{15}} & \frac{0}{m_{11}-m_{15}} \\ \frac{m_{21}-m_{25}}{m_{21}-m_{25}} & \frac{m_{22}-m_{25}}{m_{21}-m_{25}} & \frac{m_{23}-m_{25}}{m_{21}-m_{25}} & \frac{m_{24}-m_{25}}{m_{21}-m_{25}} & \frac{0}{m_{21}-m_{25}} \\ \frac{m_{31}-m_{35}}{m_{31}-m_{35}} & \frac{m_{32}-m_{35}}{m_{31}-m_{35}} & \frac{m_{33}-m_{35}}{m_{31}-m_{35}} & \frac{m_{34}-m_{35}}{m_{31}-m_{35}} & \frac{0}{m_{31}-m_{35}} \\ \frac{0}{m_{43}-m_{41}} & \frac{m_{42}-m_{41}}{m_{43}-m_{41}} & \frac{m_{43}-m_{41}}{m_{43}-m_{41}} & \frac{m_{44}-m_{41}}{m_{43}-m_{41}} & \frac{m_{45}-m_{41}}{m_{43}-m_{41}} \\ \frac{0}{m_{55}-m_{51}} & \frac{m_{52}-m_{51}}{m_{55}-m_{51}} & \frac{m_{53}-m_{51}}{m_{55}-m_{51}} & \frac{m_{54}-m_{51}}{m_{55}-m_{51}} & \frac{m_{55}-m_{51}}{m_{55}-m_{51}} \end{bmatrix} \tag{13}$$

$$\mathbf{R_H} = \begin{bmatrix} 1 & 2 & 2 & 2 & 0 \\ 1 & 2 & 2 & 2 & 0 \\ 1 & 2 & 2 & 2 & 0 \\ 0 & 2 & 1 & 2 & 2 \\ 0 & 2 & 2 & 2 & 1 \end{bmatrix} \tag{14}$$

Reduction of column elements also constitute the same concept of the algorithm. The process was applied on every column elements vertically. Let the minimum element values be represented by the row vector **c,** that is:

$$\boldsymbol{c_{min}} = [m_{51} \quad m_{52} \quad m_{53} \quad m_{14} \quad m_{15}] \tag{15}$$

We then let the maximum element values be represented by the row vector $\boldsymbol{c_{max}}$, that is:

$$\boldsymbol{c_{max}} = [m_{11} - m_{51} \;\; m_{12} - m_{52} \;\; m_{13} - m_{53} \;\; m_{54} - m_{14} \;\; m_{55} - m_{15}] \tag{16}$$

The resultant matrix $\mathbf{R_V}$ (Vertical matrix) was then derived as:

$$\mathbf{R_V} = \begin{bmatrix} 1 & 1 & 1 & 0 & 0 \\ 2 & 2 & 2 & 2 & 2 \\ 2 & 2 & 2 & 2 & 2 \\ 2 & 2 & 2 & 2 & 2 \\ 0 & 0 & 0 & 1 & 1 \end{bmatrix} \tag{17}$$

The obtained resultant matrices $\mathbf{R_H}$ and $\mathbf{R_V}$ were then used to represent a unique letter in American Sign Language Fingerspelling. In the formed resultant matrices, only the order of zeroes and ones elements within the matrices were *significant.*

In general, every letter of the American Sign Language Fingerspelling has a unique reference matrix in the system program. In order for the system to recognize a letter, the *order of zeroes and ones* of the resultant Horizontal Matrix *or* Vertical Matrix generated from the hand gesture of the user must *match* the *order of zeroes and ones* of the reference matrix corresponding to a unique letter in American Sign Language Fingerspelling.

The matching process of the algorithm is done by subtracting the generated resultant matrix and the reference resultant matrix. If the difference of the two matrices is a null matrix $\mathbf{M}_{null}$, then the generated resultant matrix has matched the expected matrix for that particular letter and therefore, the letter is recognized.

That is, for instance in the recognition of *letter A:*

$$\mathbf{R}_{\mathbf{H}_{reference}} - \mathbf{R}_{\mathbf{H}_{generated}} = \mathbf{M}_{null} \tag{18}$$

or

$$\mathbf{R}_{\mathbf{V}_{reference}} - \mathbf{R}_{\mathbf{V}_{generated}} = \mathbf{M}_{null} \tag{19}$$

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$$\begin{bmatrix} 1 & 2 & 2 & 2 & 0 \\ 1 & 2 & 2 & 2 & 0 \\ 1 & 2 & 2 & 2 & 0 \\ 0 & 2 & 1 & 2 & 2 \\ 0 & 2 & 2 & 2 & 1 \end{bmatrix} - \begin{bmatrix} 1 & 2 & 2 & 2 & 0 \\ 1 & 2 & 2 & 2 & 0 \\ 1 & 2 & 2 & 2 & 0 \\ 0 & 2 & 1 & 2 & 2 \\ 0 & 2 & 2 & 2 & 1 \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix} \tag{20}$$

$$\begin{bmatrix} 1 & 1 & 1 & 0 & 0 \\ 2 & 2 & 2 & 2 & 2 \\ 2 & 2 & 2 & 2 & 2 \\ 2 & 2 & 2 & 2 & 2 \\ 0 & 0 & 0 & 1 & 1 \end{bmatrix} - \begin{bmatrix} 1 & 1 & 1 & 0 & 0 \\ 2 & 2 & 2 & 2 & 2 \\ 2 & 2 & 2 & 2 & 2 \\ 2 & 2 & 2 & 2 & 2 \\ 0 & 0 & 0 & 1 & 1 \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix} \tag{21}$$

The researchers had set several conditions in obtaining the resultant Reference Matrix to be used in the recognition of American Sign Language Fingerspelling.

B. Determining the Reliability of the System

To obtain the reliability of the system in recognizing every letter of American Sign Language Fingerspelling, the researchers conducted four (4) sets of trials involving different users that performed fingerspelling on the system, not including the researchers who performed fingerspelling in obtaining the resultant matrix which served as the reference matrix in the recognition of the letters.
Each user then performed seventy-six (76) trial observations for every letter in ASL fingerspelling. This number of trial observations was based on the previous study.
During the test, the total number of successful recognitions were recorded along with the total number of trials performed. The formula below was used in order to obtain the percentage of the reliability of recognition:

$$Recognition = \frac{total\ no.of\ successful\ recognitions}{total\ no.of\ trials} x100\% \tag{22}$$

The researchers had also set conditions to be considered whether a certain trial observation is a success or a failure.

III. RESULTS AND DISCUSSION

A. Resultant Matrices

From the acquired joint coordinates, the researchers were able to generate two initial matrices, namely the Distal Matrix and Proximal Matrix. They were formed from the five hand fingers with corresponding 3D vector *x*, *y*, and *z*-coordinates.

TABLE I
DISTAL MATRIX OF LETTERS A AND S

Letters	Distal Matrix
A	$\mathbf{D}_A = \begin{bmatrix} -53.3519 & -24.9242 & -24.146 \\ -19.7553 & -43.3237 & -7.2154 \\ -10.7831 & -47.7051 & -5.9302 \\ 5.373228 & -46.9761 & -7.8980 \\ 19.84522 & -37.2877 & -7.2482 \end{bmatrix}$
S	$\mathbf{D}_S = \begin{bmatrix} -18.13947 & -50.4975 & -7.655 \\ -18.6076 & -48.2355 & 4.1458 \\ -10.4985 & -51.43 & 10.603 \\ 1.695625 & -46.1707 & 14.457 \\ 15.95667 & -38.7488 & 9.5208 \end{bmatrix}$

TABLE II
PROXIMAL MATRIX OF LETTERS A AND S

Letters	Proximal Matrix

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A	$P_A = \begin{bmatrix} -48.7503 & -24.7176 & -5.57548 & 15.7088 \\ -16.6092 & -17.0044 & -16.91 & -14.3807 \\ 0.550156 & -28.678 & -30.4112 & -26.530 \end{bmatrix}$
S	$P_S = \begin{bmatrix} -31.21829 & -22.5971 & -5.99134 & 12.965 \\ -38.88016 & -17.5097 & -17.6584 & -15.90 \\ 4.525692 & -22.5166 & -21.7601 & -16.432 \end{bmatrix}$

Table 1 and Table 2 shows the Distal Matrix and Proximal Matrix of sample letters A and S respectively. However, for the *dynamic* letters *J* and *Z*, the researchers obtained multiple sets of distal and proximal matrices. Hence, there is a need to match series of matrices in order to recognize the movement of these letters. With this, there will be multiple distal, proximal, output, and resultant matrices for letters J and Z.

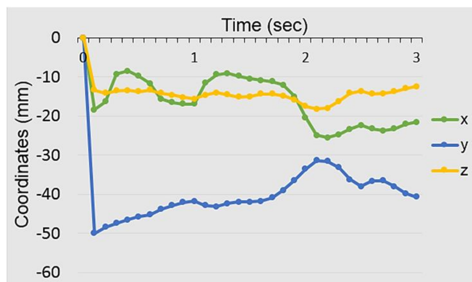

Fig. 3 Distal joint coordinates versus time graph of letter S

The joint coordinates acquired were then analyzed by the researchers. Figure 3 shows the graphical interpretation of the values of *x*, *y* and *z-coordinates* of distal joint of the thumb finger while performing the fingerspelling for letter S, as an example, within a thee-second time frame. The graph shows that there are random variations in the values of the joint coordinates showing some instability due to unstable detection of the Leap Motion Controller sensor even though there is no such movement in the actual testing performed by the user.

TABLE III
OUTPUT MATRIX OF LETTERS A, E, M, N, S, AND T

LETTERS	OUTPUT MATRIX
A	$\begin{bmatrix} 3001.603 & 2435.011 & 1453.239 & 160.94 \\ 1678.674 & 1431.92 & 1062.177 & 504.1 \\ 1314.759 & 1247.797 & 1047.159 & 673.9 \\ 513.9413 & 892.4862 & 1004.595 & 969.4 \\ -352.13 & 351.3924 & 740.3146 & 1040. \end{bmatrix}$
E	$\begin{bmatrix} 2300.834 & 893.6119 & 688.2107 & 298.93 \\ 1872.467 & 2773.33 & 2419.484 & 1492. \\ 1671.615 & 2590.782 & 2549.185 & 1935.0 \\ 939.147 & 1988.719 & 2438.656 & 2387.9 \\ 290.8077 & 1133.178 & 1818.473 & 2163.5 \end{bmatrix}$

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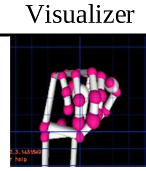
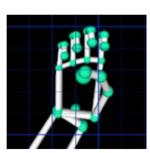
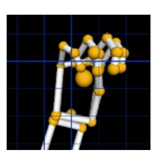
M	$\begin{bmatrix} 1431.607 & 963.5295 & 1107.627 & 1109.3 \\ 1605.81 & 1228.882 & 914.6431 & 453.5 \\ 1625.037 & 952.2344 & 771.9872 & 469.51 \\ 1401.151 & 581.6136 & 673.9973 & 673.96 \\ 999.854 & 127.8547 & 468.0085 & 759.26 \end{bmatrix}$

LETTERS	OUTPUT MATRIX
N	$\begin{bmatrix} 1423.809 & 1436.588 & 1597.358 & 1300. \\ 1750.08 & 2299.331 & 1852.114 & 957.2 \\ 1794.079 & 1939.097 & 1750.752 & 1169. \\ 1737.309 & 233.6392 & 261.2104 & 732.9 \\ 1351.339 & -33.2986 & 283.1684 & 875.7 \end{bmatrix}$
S	$\begin{bmatrix} 2494.988 & 1466.462 & 1166.961 & 693.68 \\ 2475.063 & 1171.717 & 873.0325 & 457.72 \\ 2375.342 & 899.0013 & 740.3348 & 507.54 \\ 1807.617 & 444.5875 & 490.5463 & 518.67 \\ 1051.507 & 103.5298 & 381.4655 & 666.66 \end{bmatrix}$
T	$\begin{bmatrix} 1439.094 & 1496.192 & 1200.479 & 714.71 \\ 1650.204 & 1178.284 & 908.3671 & 517.6 \\ 1513.539 & 840.076 & 697.7738 & 480.83 \\ 1085.179 & 373.4453 & 426.7036 & 455.45 \\ 612.6772 & 126.059 & 347.7241 & 553.12 \end{bmatrix}$

TABLE IV

HORIZONTAL AND VERTICAL MATRIX OF LETTERS A, E, M, N, S, AND T

RESULTANT MATRIX			
Finger-spelling Letters	Leap Motion SDK Visualizer	Horizontal Matrix	Vertical Matrix
		$\begin{bmatrix} 1 & 2 & 2 & 2 \\ 2 & 1 & 2 & 2 \\ 2 & 1 & 2 & 2 \\ 0 & 2 & 2 & 2 \\ 0 & 2 & 2 & 2 \end{bmatrix}$	$\begin{bmatrix} 1 & 1 & 1 & 0 \\ 2 & 2 & 2 & 2 \\ 2 & 2 & 2 & 2 \\ 2 & 2 & 2 & 2 \\ 0 & 0 & 0 & 1 \end{bmatrix}$
		$\begin{bmatrix} 1 & 2 & 2 & 2 \\ 2 & 1 & 2 & 2 \\ 0 & 2 & 1 & 2 \\ 0 & 2 & 2 & 1 \\ 0 & 2 & 2 & 2 \end{bmatrix}$	$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 2 & 1 & 2 & 2 \\ 2 & 2 & 1 & 2 \\ 2 & 2 & 2 & 1 \\ 0 & 2 & 2 & 2 \end{bmatrix}$
		$\begin{bmatrix} 1 & 0 & 2 & 2 \\ 1 & 2 & 2 & 2 \\ 1 & 2 & 2 & 2 \\ 1 & 0 & 2 & 2 \\ 2 & 0 & 2 & 2 \end{bmatrix}$	$\begin{bmatrix} 2 & 2 & 2 & 1 \\ 2 & 1 & 2 & 0 \\ 2 & 2 & 0 & 2 \\ 1 & 2 & 1 & 2 \\ 0 & 0 & 2 & 2 \end{bmatrix}$

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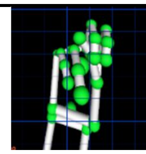
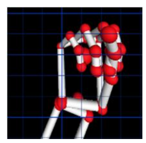
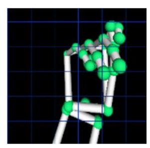
RESULTANT MATRIX			
Finger-spelling Letters	Leap Motion SDK Visualizer	Horizontal Matrix	Vertical Matrix
		$\begin{bmatrix}1&2&2&2\\1&2&2&2\\1&2&2&2\\1&0&2&2\\2&0&2&2\end{bmatrix}$	$\begin{bmatrix}2&2&1&1\\2&1&2&2\\1&2&2&2\\2&2&2&0\\0&0&0&2\end{bmatrix}$
		$\begin{bmatrix}1&2&2&2\\1&2&2&2\\1&2&2&2\\1&0&2&2\\2&0&2&2\end{bmatrix}$	$\begin{bmatrix}1&1&1&1\\2&2&2&0\\2&2&2&2\\2&2&2&2\\0&0&0&2\end{bmatrix}$
		$\begin{bmatrix}2&1&2&2\\1&2&2&2\\1&2&2&2\\1&0&2&2\\2&0&2&2\end{bmatrix}$	$\begin{bmatrix}2&1&1&1\\1&2&2&2\\2&2&2&0\\2&2&2&2\\0&0&0&2\end{bmatrix}$

Table 3 shows the obtained output matrix for the letters A, E, M, N, S, and T. It is the initial matrix used to represent the letters in American Sign Language Fingerspelling.

The fingerspelling of the letters A, E, M, N, S, and T share a common hand feature. They were grouped since all these letters have their index finger, middle finger, ring finger, and little finger closed but with their closed thumb placed in different places. As shown in Table 4, the obtained Horizontal and Vertical Matrix of these letters are distinct and unique compared to other letter matrices. These matrix pattern are then used for the recognition of the letters to increase the recognition rate and avoid misclassification.

As such, the letters M and N have distinct element values on first row in the Horizontal matrix, and distinct element values on first, third and fourth columns in Vertical matrix. Analyzing the resultant matrices of the letters S and T, they have distinct element values on first row in the Horizontal matrix, and distinct element values on first and fourth columns in Vertical matrix.

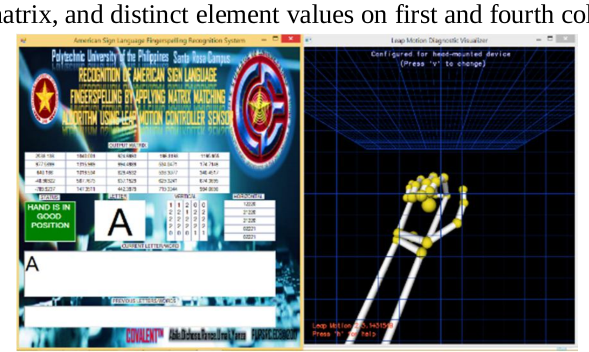


Fig. 4 Recognition of letter A

Table 5 shows the differences between the reference matrices of the letters A, E, M, N, S, and T and the generated resultant matrix of letter A. And based on the algorithm, *letter A* will then be recognized by the system since the resulted difference between the matrices is a *null matrix*. The recognized letter A is shown in Figure 4.

The obtained resultant matrices for the 26 letters of American Sign Language Fingerspelling are unique and distinct, and hence used by the researchers to distinguish and recognize them correctly.

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TABLE V

DIFFERENCE BETWEEN THE REFERENCE RESULTANT MATRIX OF LETTERS A, E, M, N, S, AND T AND THE GENERATED RESULTANT MATRIX OF LETTER A

Letter	Generated Horizontal Resultant Matrix	Reference Horizontal Resultant Matrix	Difference
A	$\begin{bmatrix} 1 & 2 & 2 & 2 \\ 2 & 1 & 2 & 2 \\ 2 & 1 & 2 & 2 \\ 0 & 2 & 2 & 2 \\ 0 & 2 & 2 & 2 \end{bmatrix}$	$R_{A=}\begin{bmatrix} 1 & 2 & 2 & 2 \\ 2 & 1 & 2 & 2 \\ 2 & 1 & 2 & 2 \\ 0 & 2 & 2 & 2 \\ 0 & 2 & 2 & 2 \end{bmatrix}$	$\begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}$
		$R_{E=}\begin{bmatrix} 1 & 2 & 2 & 2 \\ 2 & 1 & 2 & 2 \\ 0 & 2 & 1 & 2 \\ 0 & 2 & 2 & 1 \\ 0 & 2 & 2 & 2 \end{bmatrix}$	$\begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ -2 & 1 & -1 & 0 \\ 0 & 0 & 0 & -1 \\ 0 & 0 & 0 & 0 \end{bmatrix}$
		$R_{M=}\begin{bmatrix} 1 & 0 & 2 & 2 \\ 1 & 2 & 2 & 2 \\ 1 & 2 & 2 & 2 \\ 1 & 0 & 2 & 2 \\ 2 & 0 & 2 & 2 \end{bmatrix}$	$\begin{bmatrix} 0 & -2 & 0 & 0 \\ -1 & 1 & 0 & 0 \\ -1 & 1 & 0 & 0 \\ 1 & -2 & 0 & 0 \\ 2 & -2 & 0 & 0 \end{bmatrix}$
		$R_{N=}\begin{bmatrix} 1 & 2 & 2 & 2 \\ 1 & 2 & 2 & 2 \\ 1 & 2 & 2 & 2 \\ 1 & 0 & 2 & 2 \\ 2 & 0 & 2 & 2 \end{bmatrix}$	$\begin{bmatrix} 0 & 0 & 0 & 0 \\ -1 & 1 & 0 & 0 \\ -1 & 1 & 0 & 0 \\ 1 & -2 & 0 & 0 \\ 2 & -2 & 0 & 0 \end{bmatrix}$
		$R_{S=}\begin{bmatrix} 1 & 2 & 2 & 2 \\ 1 & 2 & 2 & 2 \\ 1 & 2 & 2 & 2 \\ 1 & 0 & 2 & 2 \\ 2 & 0 & 2 & 2 \end{bmatrix}$	$\begin{bmatrix} 0 & 0 & 0 & 0 \\ -1 & 1 & 0 & 0 \\ -1 & 1 & 0 & 0 \\ 1 & -2 & 0 & 0 \\ 2 & -2 & 0 & 0 \end{bmatrix}$
		$R_{T=}\begin{bmatrix} 2 & 1 & 2 & 2 \\ 1 & 2 & 2 & 2 \\ 1 & 2 & 2 & 2 \\ 1 & 0 & 2 & 2 \\ 2 & 0 & 2 & 2 \end{bmatrix}$	$\begin{bmatrix} 1 & -1 & 0 & 0 \\ -1 & 1 & 0 & 0 \\ -1 & 1 & 0 & 0 \\ 1 & -2 & 0 & 0 \\ 2 & -2 & 0 & 0 \end{bmatrix}$

B. Reliability of the System

The system recognition reliability was shown in Table 6 indicating the average recognition rate for every letter in American Sign Language Fingerspelling obtained from the test recognition result performed by the four users. It can be noted that the letters B, L, Q, W, and Y obtained the highest average recognition rate which is perfectly 100.00 %. This is generally because of the uniqueness of the letters' static hand gesture compared to other letters. Specifically the letters' static hand gesture are fingerspelled open and wide, and formed with the fingers involved separate from each other. Hence generating a more unique and distinct resultant matrix pattern compared to other letters.

On the other hand the lowest average recognition rate is 85.86 % which corresponds to letter M. This is because the Leap Motion Controller Sensor finds it difficult to locate the thumb and some overlapping fingers during actual testing that led to misclassification. In general, the system's reliability in recognizing letters in ASL Fingerspelling in average is 94.86 %.

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TABLE VI

AVERAGE RECOGNITION RATE FOR EVERY LETTER IN ASL FINGERSPELLING

SYSTEM RECOGNITION RELIABILITY	
ASL Letters	Average Recognition Rate
A	97.70 %
B	100.00 %
C	95.72 %
D	95.39 %
E	96.71 %
F	96.05 %
G	90.46 %
H	92.11 %
I	96.71 %
J	91.45 %
K	96.05 %
L	100.00 %
M	85.86 %
N	86.18 %
O	91.45 %
P	94.41 %
Q	100.00 %
R	99.01 %
S	92.11 %
T	93.09 %
U	95.72 %
V	96.71 %
W	100.00 %
X	96.05 %
Y	100.00 %
Z	87.50 %

Table 7 shows the average recognition rate of every user in the test recognition they had performed. It can be seen that the highest average recognition rate is 96.0526 % performed by User 1. Generally, the overall system reliability is **94.8634 %** based on the result.

TABLE VII

SYSTEM RECOGNITION RELIABILITY SHOWING THE AVERAGE RECOGNITION RATE FOR EVERY USER

SYSTEM RECOGNITION RELIABILITY	
USER	Average Recognition Rate
1	96.0526 %
2	94.8381 %
3	93.9777 %
4	94.5850 %
Average	94.8634 %

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IV. CONCLUSIONS

Based from the data gathered, the formed output matrices for the letters of American Sign Language Fingerspelling are distinct. However, there are some letters having their output matrix elements close to other letters' matrix elements. Also, during the joint coordinate acquisition, some discrepancies such as improper positioning and unnecessary motions of the fingers between the actual appearance of user's hand gesture while performing Fingerspelling and its graphical representation in Leap Motion Sensor visualizer can be observed. This problem causes unstable reading and unwanted variations in the values of the joint coordinates needed to form the necessary resultant matrices which could result to misclassification.

Most of the letters were recognized by the system resulting to a desirable overall reliability. However, undesirable results had been observed for letters M and N having the lowest recognition rates. This problem is mainly due to the failure of Leap Motion Controller sensor to properly detect joints of overlapping fingers of closed hands and/or actual positioning of the fingers while performing fingerspelling for these letters. On the other hand, the average recognition rates for letters having dynamic hand gestures J and Z are quite lower than average recognition rates of most of the letters having static hand gestures. Since the system is designed to generate and match multiple resultant matrices to recognize hand movements while performing fingerspelling for letters J and Z, any improper and/or unintentional movement of the fingers and the hand itself causes mismatch between the generated resultant matrices and reference resultant matrices. Notwithstanding these problems, the data gathered show that the overall reliability of the system is satisfactory and therefore, the use of Matrix Matching Algorithm is effective in recognizing the letters in American Sign Language Fingerspelling.

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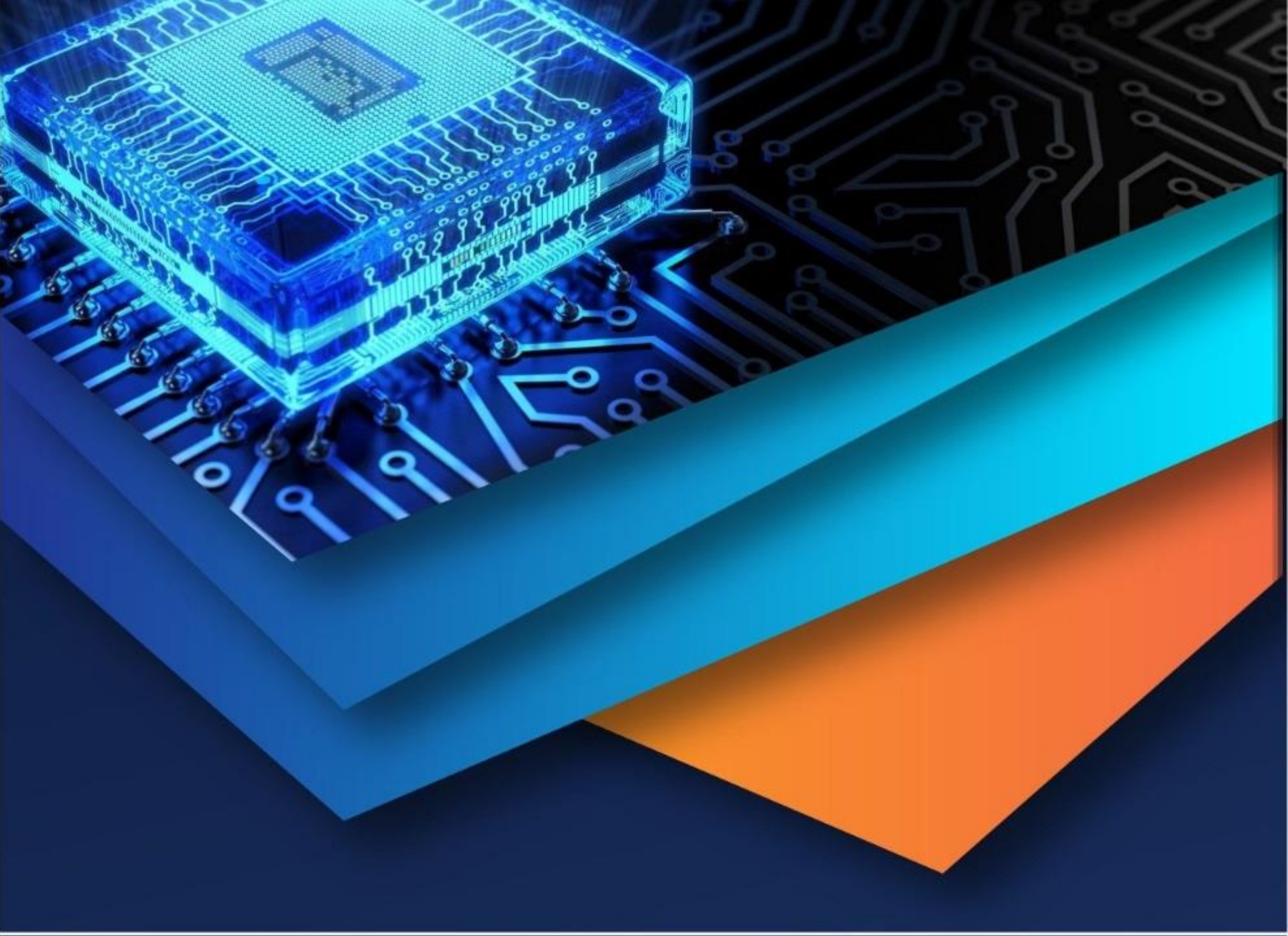

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