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RESEARCH ARTICLE

Electric Wheelchair Control Using Wrist Rotation Based on Analysis of Muscle Fatigue

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ABSTRACT The wheelchair is one of the most common assistive technologies for people with motor impairment, due to its environmentally friendly features in terms of mobility and comfort. However, the operational method for the conventional wheelchair is still inconvenience for people with finger problems. Therefore, in the project, a novel control method to operate an electric wheelchair, using hand gestures (wrist rotation) is developed. Sixty-five (65) participants were involved in this study. Five hand gestures were considered and studied for forward, backward, right, left, and stop maneuvers while considering the human ergonomics factor. In this study, the stop maneuver was determined based on the most comfortable hand position to mitigate a fatigue experience, with two gesture classifying methods further investigated. The first method based on threshold has a promising accuracy of 96% and 91% precision. This method, however, requires a calibration every time a new user is introduced. The second method, a Naïve Bayes approach, was observed to solve the problem, as it has about 99% of both accuracy and precision. The evaluation of this method was then conducted with six participants that operated the wheelchair to follow the trajectories from start to end. The results showed that the participants comfortably controlled the developed wheelchair system to the goal without any collision. Results from experiments indicate that the proposed approach has high accuracy and the potential to solve the problem related to finger dependencies and hand fatigue.

INDEX TERMS Hand gesture, wrist rotation, wheelchair, fatigue, Naïve Bayes.

I. INTRODUCTION

The number of disabled patients increases due to drugs, accidents, and aging [1]. Usually, they need special rules and special auxiliary equipment such as hearing aids, visual aids, special communication devices, and special means of transportation. A wheelchair is one of the greatest assistive tools for people with special needs [2]. But in some cases, a conventional wheelchair that is operated by fingers causes dilemma for users with finger problems. Quadriplegic patients who could not control their legs and arms properly are an example of such condition. They face difficulties in their daily activities, such as eating and toilet usage. It is also difficult for them to control a wheelchair using their fingers [3], [4].

Based on these conditions, an alternative method to control wheelchairs is required to improve access for disabled patients in doing their activities. Nowadays, the conventional

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wheelchair has been developed into an intelligent wheelchair. A new model of wheelchairs is manufactured with a combination of sensors and computers [2]. Also, a joystick is used as the user interface to control wheelchairs[5]. This is categorized as a direct contact method. An intelligent touchscreen joystick using fingers is also developed [6], [7]. Recently, the indirect contact method using smart control devices [8], [9], [10], such as wireless head control [11] has been encouraged.

The indirect control method using hand gestures is one of the options for controlling the wheelchair [2], [3]. The sensors used for the recognition of this gesture are generally an accelerometer [3], a gyro [12], and a camera [2], [13]. The accelerometer and gyro sensors are usually attached to the hand. The position and orientation are captured by these sensors. The camera usually detects the subject from a distance. Both Kinect and Leap Motion have embedded camera sensors that can detect different human body gestures. As the Kinect can detect the whole body, leap motion is developed mainly to map motion from hand to fingertip [12], [14], [15].

The leap motion allows experts to develop an advanced implementation of the virtual keyboard [16], which is controlled by two fingers for five (5) tasks, which are right, left, up, down, and select [17]. As reported by [18], a combination of leap motion and a speech sensor was implemented to control a wheelchair. It is found that leap motion performs effectively at a radius and accuracy of 40 cm and 0.01 mm, respectively [2], [12], [19]. For leap motion, the joints from the elbow to the fingertips are detected, with the sensor providing a detailed 3D geometric and kinematic overview of the hand [20]. As for users without fingers, the sensor can still detect the wrist and elbow joints [21]. This is an incentive for the development of any alternative method in operating a wheelchair without fingers.

From the literature, experts have reported methods in which hand gestures are detected and classified for different purposes. These gestures are generally classified into stationary [22], [23] and dynamics [24], [25]. The recognition systems of hand gestures based on centroid points [26] are developed to control a mouse [27], and to operate a video player [28]. The hand gesture from leap motion is also used to control mobile robot [29], robot manipulator [30], flight simulation [21] and detect hand tremor [19]. Besides for head gestures [3], orientation features are also used to recognize finger signs [24]. A neural network can be developed to classify hand gestures, through the data obtained from an accelerometer, with high accuracy [31]. The Euclidean distance measured from the finger image can be applied to operate a bed position for up, down, left, and right maneuvers as reported by [1]. Subsequently, wrist orientation is found to be an alternative feature in recognizing hand gestures [23]. Wrist rotation, especially pitch and yaw variables, can be used to control mobile robot [29]. It is shown that wrist orientation can be an alternative feature to recognize hand gestures [32], which can be used to lessen finger dependencies.

Another issue arising from controlling with the hand is muscle fatigue, which causes lower precision in control ability [33]. This leads to unstable hand positions [34], therefore, increasing the noise. One of the experiments conducted to determine hand muscle fatigue is by keeping the hand in a static position [35]. This condition should be considered in controlling the machine by hand [36]. So in this study, a new mechanism using a hand wrist is developed to control an electric wheelchair. Several hand positions are further studied to determine the usual location for the stable operational hand. In addition, a leap motion sensor is adopted and used to obtain hand features, such as pitch, yaw, and roll parameters.

II. CONTRIBUTIONS

A wheelchair is an object controlled by users in this study. Some researchers developed alternative methods to control wheelchair, such as using a touch screen with a graphical user interface [7]. A study on controlling a wheelchair using leap motion is also reported [34]. The method, however, still requires fingers to control the wheelchair properly, which can be problematic for patients with finger problems. Therefore, in this project, we develop a control system for a wheelchair based on wrist orientations/movements. The system is developed by considering muscle fatigue due to exhaustion. It is set for the hand position to be in a natural position, with minimum effort to withstand the gravity force for the no movement/maneuver settings. A Naïve Bayes algorithm is developed to recognize five hand gestures for five maneuvers: forward, backward, right, left and stop.

III. METHOD

There are four main stages in this study as shown in Fig. 1. An electric wheelchair was designed with additional features such as hand sensors and a user interface monitor to control the machine. Also, the hand gesture recognition method was developed after the selection of the hand position, which was studied based on its natural and relaxed level. Subsequently, the hand gesture recognition methods and performances were investigated and analyzed, respectively. This study has ethical approval from the Ethical Research Committee of Universitas Andalas, with the decision letter No. 521/UN.16.2/KEPFK/2021.

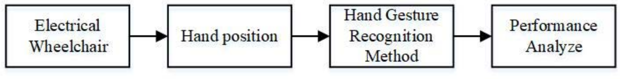


FIGURE 1. **Four steps in developing a wheelchair control system using hand gestures.**

A. ELECTRIC WHEELCHAIR SYSTEM

A system used to operate and control a motorized wheelchair through hand gestures (i.e., wrist rotation/movement) was designed in this study. The positions of the hand gestures are captured by a sensor system as the input. The position is represented by pitch, yaw and roll. A graphical user

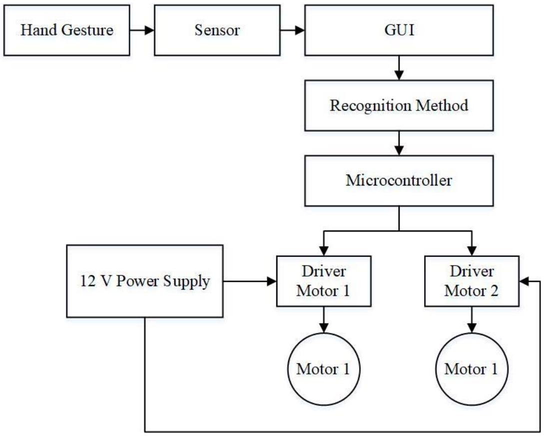


FIGURE 2. The electric wheelchair control system.

interface (GUI) is processed by a processing software and shown on a mini monitor. The hand gesture recognition algorithm is also embedded in the system. Five commands were considered, namely forward, backward, right, left, and stop. A microcontroller was used to process the command and provide the signal to two driver motors, towards conducting the necessary maneuvers. The driver motors are supplied by a 12 V electric source. Fig 2. shows the main components used to control this wheelchair.

Fig. 3 shows the schematic diagram of the developed electrical wheelchair. PCB 1 is the microcontroller board. An input signal from a computer is processed in an ATmega 328 microcontroller with a 16 MHz clock speed. This microcontroller sends the control signal to the motor drivers. There are two motor drivers for two wheels: PCB 2 and PCB 3. The integrated circuit SN74HC244DW has the buffer function before the signal comes to the BTN7970B as the H-bridge circuit. This H-bridge has a maximum output at 45 V, 50 A for 5.3 V input.

A Leap Motion Controller (LMC) is adapted to detect the 3D hand gesture toward controlling the wheelchair. Here, the proposed machine used the LMC which is set for the right hand. The location of the motion controller on the wheelchair is shown in Fig. 3. The LMC is positioned at approximately 25 cm under the right armrest to provide maximum accuracy [37].

A monitor screen is included as a display in operating the wheelchair, visualizing an application that is performed as the human-machine control interface. There are five virtual buttons in the application, namely forward, backward, right, left, and stop. The wheelchair is shown in Fig. 4.

A simple Graphical User Interface (GUI) for the application is developed, where the green and red buttons indicate activity and inactivity, respectively. As illustrated in Fig. 5, only one active button is observed.

B. HAND GESTURE

The proposed wheelchair is controlled by five static hand gestures of the right hand. This will lessen the problem of performing the position in dynamic gesture [36], [38], which can cause a low accuracy performance [8].

The control of the proposed wheelchair was based on the position determined from the wrist orientation, which was obtained using the leap motion coordinate. Furthermore, the wrist orientation was defined by three variables, pitch, yaw, and roll, along the x, y, and z-axes, respectively, as illustrated in Fig. 6.

The hand position was initially investigated for the stop button on the GUI application and considered as the reference point for other gestures in controlling the wheelchair. It was also found to be the resting point for users. Consequently, the hand position that is easily formed and maintained for a certain period should be used. Such a position should be able to mitigate errors due to muscle fatigue.

A series of investigations to determine the position for the stop point were further designed, with three candidates for comfortability shown in Figure 7(a) [19], (b) [39] and (c). The coordinates of these hand positions were captured by the leap motion and set as the reference. The pitch, yaw, and roll variables were also relative to these coordinates.

The number of participants (m) was calculated using Eq. 1 following a reference by I. Guyon *et al.* (1) [40]. The number was calculated with a 90% level of confidence, $z_\alpha = 1.28$ and 20% β-error. Data from forty (40) participants were recorded and used to train the developed algorithms. Another twenty-five (25) participants (not included in the training phase) were used in testing the algorithm.

$$m = \left(\frac{z_\alpha}{\beta}\right)^2 \tag{1}$$

They were all identified without a problem with their hand and leg conditions. The abilities of these participants to maintain the hand position based on the three wrist orientations were recorded. The data collected was also repeated thrice for each position. Moreover, a subject is considered to be tired when consciously becoming uncomfortable. In this case, the recording process was then stopped. From the data collected, the position with the longest time duration was selected as the wrist orientation for the relax position/stop position.

C. GESTURE RECOGNITION

The wheelchair is capable of five maneuvers, which are moving right, left, forward, backward, and stop. Therefore using only the wrist position as the input variable, the system requires five positions to represent the five buttons available on the GUI. Two control algorithms were developed in this research. They were the threshold value-based method and the naïve Bayesian method.

1) THRESHOLD METHOD

Wrist rotation, especially pitch and yaw variables, has been used to control the mobile robot using certain threshold values [29]. The pitch, yaw, and roll were used to determine the wrist position, as a set of threshold values was investigated.

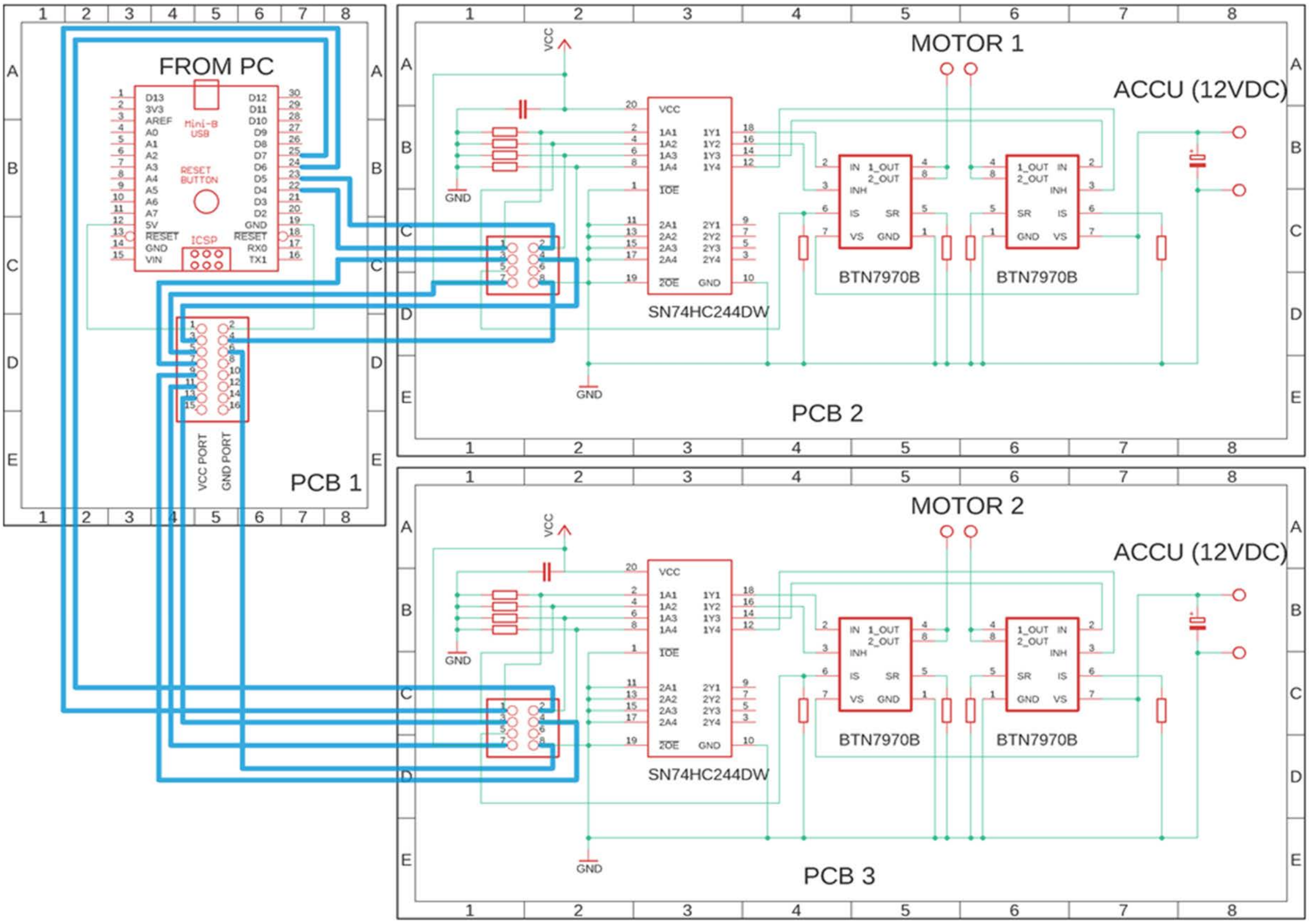


FIGURE 3. **The schematic diagram of electrical wheelchair.**

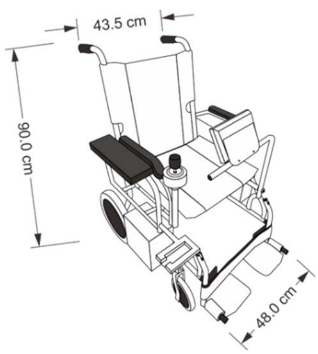


FIGURE 4. **The designed wheelchair with a monitor and a leap motion controller.**

These values were set based on being able to distinguish the required five positions, namely stop, forward, backward, left, and right. The boundary parameters of the threshold values were also determined using Eq. (2), (3), and (4). Where, SD = standard deviation, *"th"* = the threshold, and P, Y, and R = pitch, yaw, and roll, respectively. The normal for P, Y, and R were defined as the directions where the hand position was stable. In addition, the standard deviations of

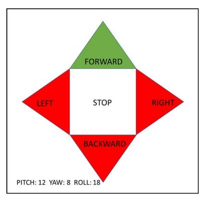


FIGURE 5. **A simple user interface for five commands to control the wheelchair.**

each variable were obtained from the experiment of setting the stop position.

$$P_{th} = P_n + SD_P \tag{2}$$

$$Y_{th} = Y_n + SD_Y \tag{3}$$

$$R_{th} = R_n + SD_R \tag{4}$$

Which:

P_{th}, Y_{th} and R_{th} = threshold pitch, yaw and roll.

P_n, Y_na nd R_n = normal for pitch, yaw and roll.

SD_P, SD_Y andSD_R = standard deviation for pitch, yaw and roll.

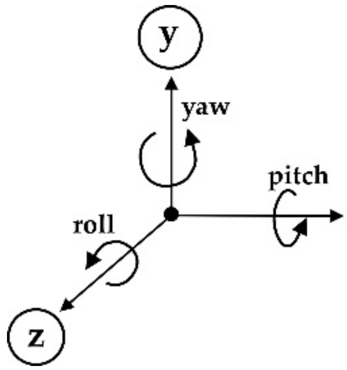


FIGURE 6. Pitch, Yaw and Roll direction of the wrist.

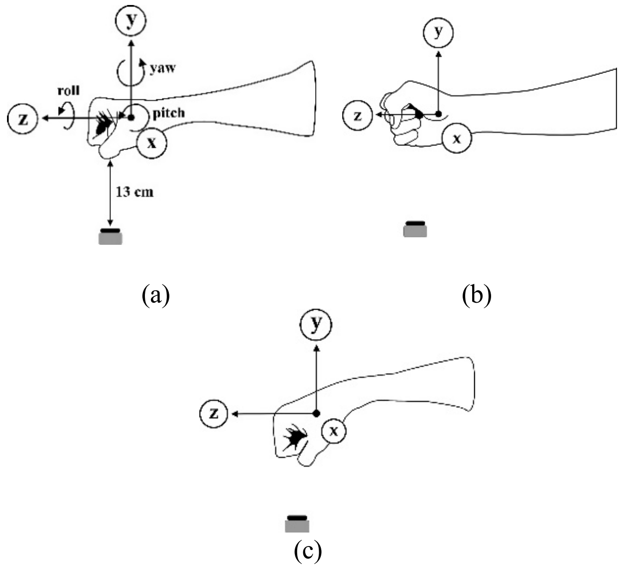


FIGURE 7. Three candidates for stop hand gesture. (a) Position 1, (b) Position 2 and (c) Position 3.

2) NAÏVE BAYESIAN METHOD

A clustering method was designed to recognize the required five gestures in this study. The Naïve Bayesian equation in Eq. (5) described the posterior probability P(C|X) as the prospect of a cluster (C) existence during the occurrence of an event (X). This indicated that the P(C|X) was equal to the probability of an event occurring in a cluster P(X|C). It was also equal to the cluster probability (P(C)) divided by the prospect of an event P(X).

$$P(C|X) = \frac{P(X|C)\,P(C)}{P(X)} \tag{5}$$

In this study, three variables(pitch (X_1), yaw (X_2), roll (X_3)) instigated the emergence of the cluster. Furthermore, Eq. (6) calculates the probability of a gesture belonging to a certain cluster, due to its pitch, yaw, and roll. The cluster having the biggest probability was further associated with the respective hand gesture. The flowchart of the algorithm to classify the hand gesture is illustrated in Fig. 8.

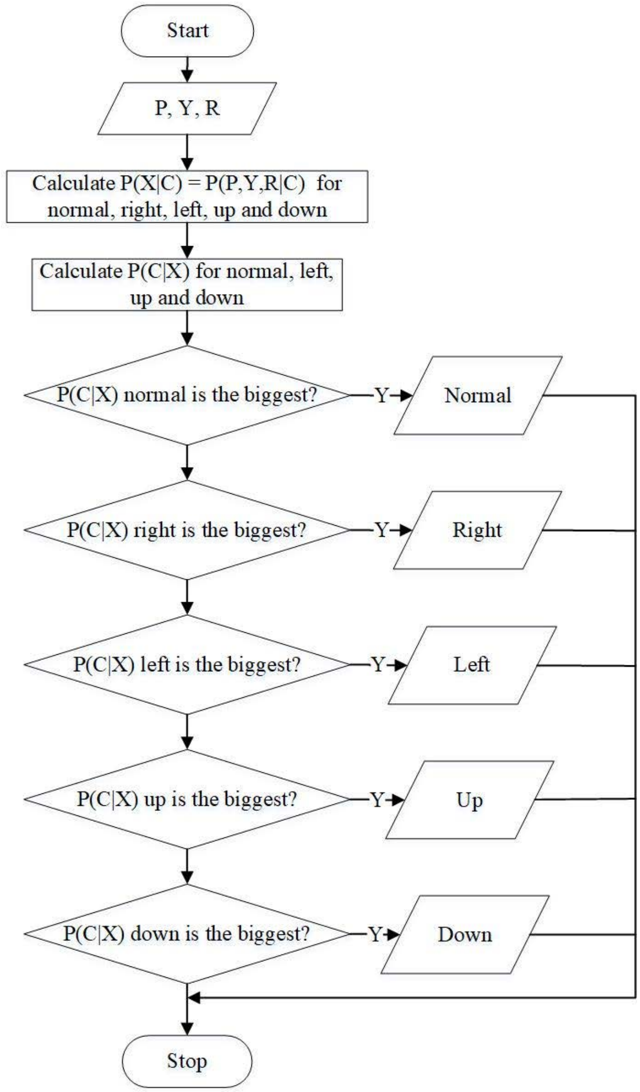


FIGURE 8. The algorithm to clustering the hand gesture using naïve bayesian method.

$$P(C|X_1, X_2, X_3) = P(C) \prod_{i=1}^{3} P(X_i|C) \tag{6}$$

The probability of the variables in a gesture (P(X|C)) is calculated using Eq. (7).

$$P(X|C) = \frac{1}{\sqrt{2\pi\sigma_{ij}}} e^{-\frac{(x_i-\mu_i)^2}{2\sigma_{ij}^2}} \tag{7}$$

where

i	variables which 1 = pitch, 2 = yaw and 3 = roll
j	cluster which 1 = stop, 2 = forward, 3 = backward, 4 = right, 5 = left.
σ_{ij}	standard deviation of variable i for cluster j
x_i	probability of variables i
μ_i	average probability of variable i

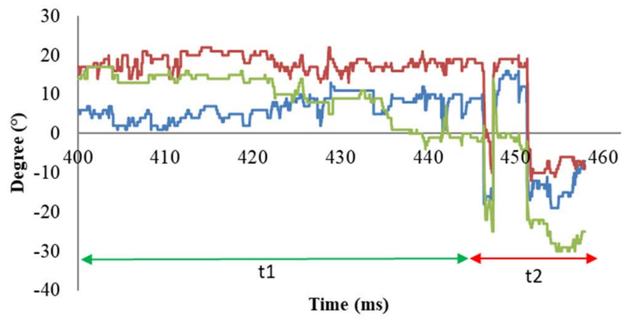


FIGURE 9. Example of Pitch, Yaw and Roll signals for position 1.

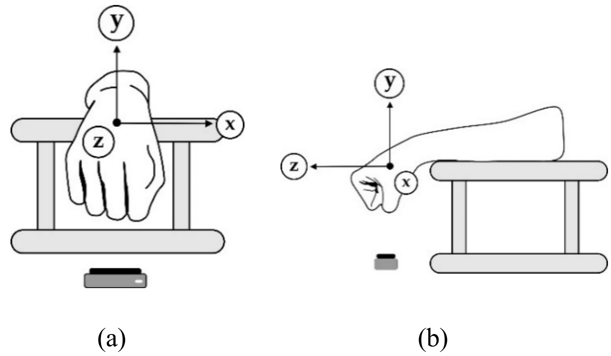


FIGURE 10. Hand position for stop (Position 3), (a) Front view and (b) Side view.

TABLE 1. Duration of hand can be maintained (second).

	Position		
	1	2	3
Mean	174	167	662
SD	89	55	139
Max	324	339	1087
Min	55	68	505

TABLE 2. Sign of variable for hand gestures.

Variable	Gesture			
	Forward	Backward	Right	Left
Pitch	+	-	+	+
Yaw	-	+	+	-
Roll	+	+	-	+

D. EVALUATION METRICS

The performance of the recognition method is evaluated with a confusion matrix in which the predictive hand gestures are compared. There are 40 and 25 participants for the training and testing experiment, respectively. Each participant performs five (5) gestures, eighteen (18) times repeatedly. So, a gesture will have 720 training data and 450 testing data. There are six indicators used for estimating the information retrieval: precision or positive predictive value (PPV), recall or true positive value (TPR), selectivity or true negative rate (TNR), F1 Score (F1) [41], [42], [43], [44], accuracy (ACC) [45].

IV. RESULT AND DISCUSSION

A. HAND POSITIONS

Figure 9 shows samples of pitch, yaw and roll signals from 400 milliseconds to 460 milliseconds. The signal in *t1* period is a signal pattern when the volunteer can still maintain the hand position. *t2* indicates that the hand is no longer in the desired position. The sudden change without an intention to change the hand position should be avoided to prevent signal errors in operating the wheelchair.

Table 1 provides the average duration of 40 volunteers in maintaining hand conditions for three proposed positions. The result showed that the best performance was in the 3rd position, where the participants endured for more than 10 mins. This was much better than positions 1 and 2, which only lasted for about 3 mins. The position supporting the reduction of the muscle fatigue risks was also very important in the design. Therefore, position 3 is selected as the reference gesture for stop, as shown in Fig. 10.

Based on the establishment of the stop hand position, four orientations were still required to control the wheelchair, including the forward, backward, right, and left maneuvers. Figure 10(a) and (b) are the positions for forward and backward maneuvers, having a clockwise and counter-clockwise rotation along the x-axis, respectively. The right and left turns of the wheelchair were further derived from the hand rotations along the z-axis. In addition, the clockwise and counter-clockwise rotations along the z-axis are shown for the right and left turns in Fig. 11(c) and(d), respectively.

Further experiments were conducted to determine the pattern of pitch, yaw, and roll signals when the hand gesture relatively changed to the stop position. Figure 12 shows these variables when the hand gesture changes from the stop to the right. The stop maneuver started from 3 to 6 secs and was marked by *t1* period. After 6 secs, it went to *t2*, as the hand rotated along the z-axis to perform the right gesture.

When the variable value after the movement was bigger and smaller than normal, positive (+) and negative (-) signs were indicated, respectively. The normal value was calculated based on the data collected from the volunteers. For this method, the complete table for each hand gesture is shown in Table 2. It can be observed that the forward and left maneuvers had similar signs, indicating a challenge to determine the motion only with this information.

The characteristics of all variables for the four hand gestures were analyzed, with the volunteers performing each action 18 times. The results are shown in Table 3. Moreover, the pitch was averagely negative for all gestures, as the hand orientation was downward due to gravity. This direction reduced the effort to withstand the gravity force. Also, almost all gestures had positive yaw, except the left maneuver, indicating that the hand position was identical to the normal

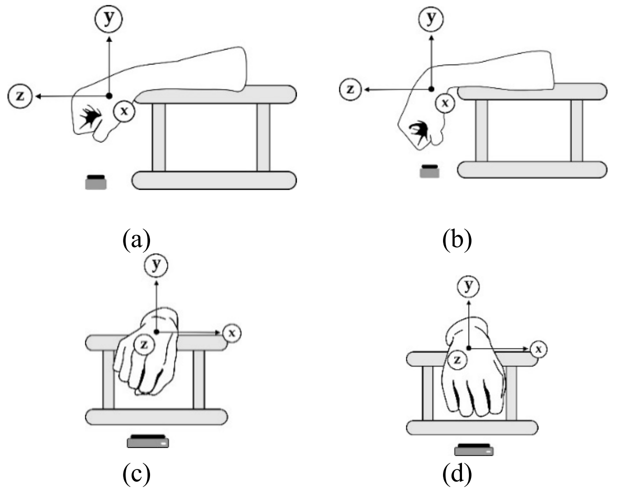


FIGURE 11. Hand position (a) forward (b)backward, (c) left and (d) right.

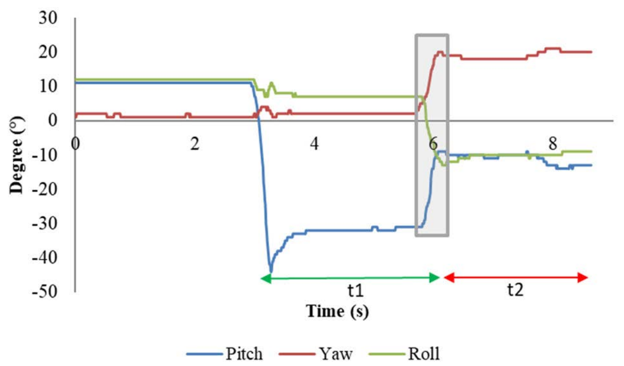


FIGURE 12. The pitch, yah and roll from stop to the right.

TABLE 3. Characteristic of variable.

Variable		Gesture				
		Stop	Forward	Backward	Right	Left
Mean	P	-24°	23°	-51°	-25°	-18°
	Y	9 °	8°	14°	40°	-16°
	R	11°	14°	23°	10°	26°
SD	P	4°	9°	11°	11°	11°
	Y	6°	7°	10°	8°	7°
	R	8°	9°	15°	11°	15°
Max	P	-11°	62°	-30°	12°	16°
	Y	26°	27°	33°	68°	-3°
	R	34°	-79°	70°	41°	64°
Min	P	-39°	-79°	7°	-53°	-42°
	Y	-5°	-13°	-9°	26°	-45°
	R	-9°	-9°	-9°	-26°	-13°

orientation for the forward, backward, and right conditions. However, the hand moved in the opposite direction for the left gesture.

B. HAND GESTURE RECOGNITION

An algorithm based on the threshold method was determined using the signs and standard deviation of the variables. The first gesture to be analyzed was the backward maneuver, due to being the only condition with a negative sign for the pitch. The algorithm will next check the right gesture when the signal did not meet the backward condition. Besides the stop, only three possible gestures were observed when the maneuver was not in a backward condition. Among these three, the right maneuver was the only gesture with a positive change in the yaw value. For that reason, this variable is used to detect the right gesture. The forward and left gestures were then distinguished based on the pitch value. According to the experiment, the average pitches for the forward and left gestures were positive and negative, respectively. The gesture was assumed as the stop position when all conditions were not met. The algorithm based on the threshold method is shown in Fig. 13.

The confusion matrix of the threshold method is given in Table 4. The accuracy of the threshold method is also investigated using the data collected from 40 participants.

TABLE 4. Confusion matrix of threshold method.

		Prediction				
		B	R	F	L	S
Actual	B	705	8	0	2	5
	R	79	641	0	0	0
	F	0	127	590	0	3
	L	26	0	17	674	3
	S	7	41	5	27	640

B = backward, R= right, F = forward, L = left, S = Stop

TABLE 5. Performance of threshold method (%).

	B	R	F	L	S	Mean
PPV	86%	78%	96%	96%	98%	91%
TPR	98%	89%	82%	94%	89%	90%
TNR	96%	94%	99%	99%	100%	98%
F1	92%	83%	89%	95%	93%	90%
ACC	96%	93%	96%	98%	97%	96%

B = backward, R= right, F = forward, L = left, S = Stop

TABLE 6. Confusion matrix of naïve bayes method in training data.

			Prediction				
			B	R	F	L	S
Actual	Training	B	717	3	0	0	0
		R	0	707	0	7	6
		F	0	0	719	0	1
		L	0	5	0	715	0
		S	0	3	0	0	717
	Testing	B	440	2	0	2	6
		R	0	438	0	11	5
		F	0	0	450	0	0
		L	0	0	0	450	0
		S	0	0	0	0	450

B = backward, R= right, F = forward, L = left, S = Stop

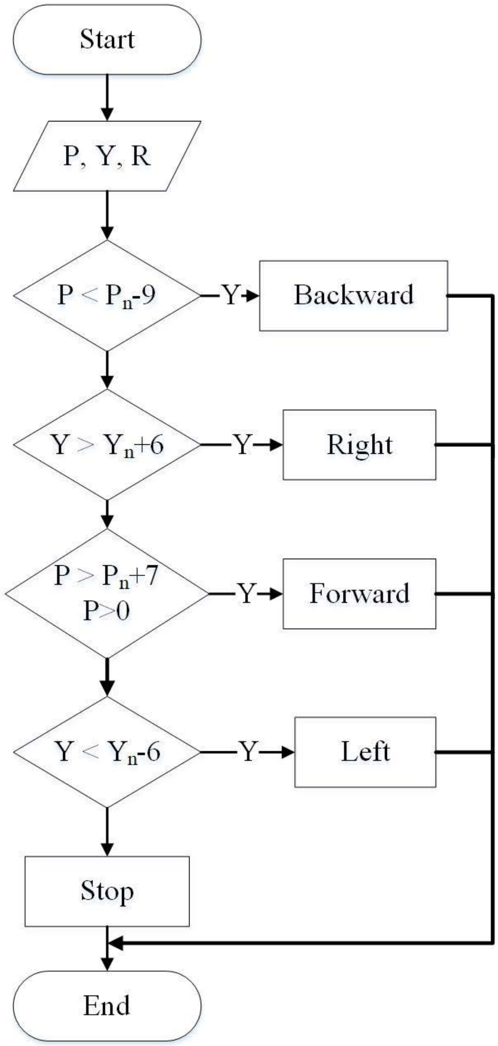


FIGURE 13. A threshold based algorithm.

As participants were ordered to perform each gesture 18 times, there were 720 data for each gesture, indicating a total of 3600 motions.

The performance of the threshold method is shown in Table 5. Generally, the threshold method has high accuracy (ACC) with an average of 96%. The threshold method could differentiate between backward and forward gestures as well as the right and left gestures. There is no misinterpretation for the threshold method to recognize two opposite movements. The accuracy, however is unbalanced since the TNR is 98% and the TPR is only 90%. The threshold method records an 91% precision. Even though all right and back gestures have accuracies 96% and 93%, but both gestures have lower precisions of 86% and 78%, respectively. F1 score is 90% which indicates that the method can be improved. Another disadvantage of this method is that it requires normal variables of each volunteer/user. So, proper calibration is required every time a new user is introduced. This situation is not effective since the solution is partially general and self calibration takes time for the process [46].

TABLE 7. performance of naïve bayes method (%).

		B	R	F	L	S	Mean
Training	PPV	100%	98%	100%	98%	100%	98%
	TPR	99%	100%	100%	100%	99%	100%
	TNR	100%	99%	100%	99%	100%	99%
	F1	99%	99%	100%	99%	99%	99%
	ACC	99%	99%	100%	99%	99%	99%
Testing	PPV	97%	98%	100%	98%	97%	98%
	TPR	97%	99%	100%	100%	97%	99%
	F1	99%	98%	100%	99%	99%	99%
	ACC	100%	99%	100%	99%	100%	100%
	TNR	99%	99%	100%	99%	99%	99%

B = backward, R= right, F = forward, L = left, S = Stop

The naïve Bayes method is implemented to improve the accuracy of the system. Table 6 shows the confusion matrix of Naïve Bayes. Firstly, the method was evaluated with the same data utilized for the threshold approach. This was the training data to determine the mean and standard deviation of each gesture variable. The trained naïve Bayes parameter was then evaluated on a separate testing set. The testing set had a similar amount with the training set.

The training performance of Naïve Bayes method is shown in Table 7. Naïve Bayes method has a higher performance than threshold method with 99% accuracy. Both recall and selectivity indicators show that Naïve Bayes method could detect not only the desired gesture but also a movement not in accordance with a gesture. Naïve Bayes method also has higher precision than the threshold method, with 99% precision on average. The result shows that TNR variable of all gestures has 100% performance. This is outstanding because it indicates that the method could detect undesired gestures very well. The period of changing the hand position in the dynamic hand gesture can be one of the causes for errors to occur [47]. The shaded area, in Fig. 12, is an example of a transition period from one state to another.

The method also has no requirement for a participant to calibrate their hand position. Based on the results, the naïve Bayes has a better performance than the threshold based method. The accuracy of Naïve Bayes also produces a good performance on the testing set. The average accuracy and precision are found to be 99% and 98%, respectively in testing set. Following these findings, the Naïve Bayes method is used as the gesture recognition method for the control system of the wheelchair for the experiment in this study.

From the literature, there were several methods of hand gesture recognition have been carried out by researchers, as shown in Table 8. The methods to classify the hand gestures are Convolutional Neural Network (CNN) [22], Euclidian distance method [1], [2] threshold method [17], [18] and Feedforward Neural Network [31]. Using the reflected

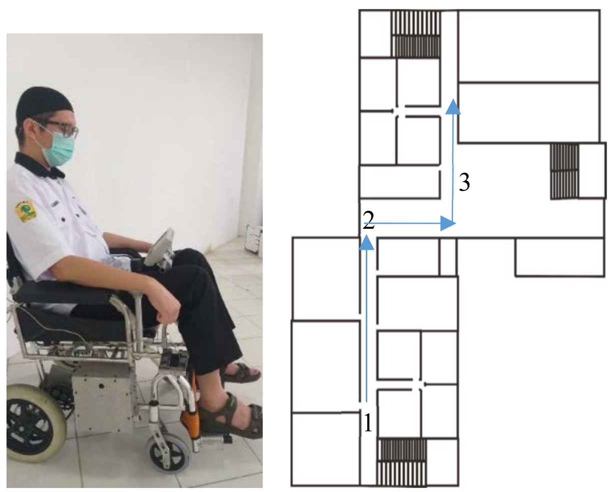
TABLE 8. **Hand gesture recognition methods compared to the proposed method.**

Feature	Number of Gesture	Classifier	Result
Reflected Impulse from hand gesture [22]	6	Convolutional Neural Network	This method has 0.90 accuracy to control the wheelchair
Hu invariants as Geometric Parameters of hand [2]	4	Euclidian Distance	Hand gesture from a camera controls a wheelchair. But this method still has robustness issues.
Finger coordinate [17]	5	Threshold	Finger gesture operates the virtual keyboard
Hand position (combine with speech) [18]	3	Threshold	Three hand positions can control the virtual keyboard.
Kinematic characteristics of hand gesture [31]	24	Feedforward Neural Network	This method has about 0.99 accuracy using an accelerometer.
Area, Eccentricity and Solidity of hand gesture[1]	4	Euclidean Distance	This method has 0.86 accuracy
Proposed			
Pitch, Yaw and Roll of Hand Gesture	5	Threshold	This method has 96% accuracy and 88% precision.
	5	Naïve Bayes	This method has 99% accuracy and 99% precision in controlling the wheelchair

TABLE 9. **Qualitative experiment to evaluate the designed method.**

Participant	Training		Testing	
	Con.	Com.	Con.	Com.
1	S	S	S	S
2	S	S	S	S
3	S	S	S	S
4	S	S	S	S
5	S	F	S	S
6	S	F	S	S

Con. = Controllability, Com. = Comfortability S = Success, F = Failure



(a) (b)

FIGURE 14. **(a) Participant operates the wheelchair and (b) The layout of the trajectory of the implementation wheelchair control system using hand gestures.**

impulse form, the CNN has 90% accuracy in recognizing the six gestures [22]. Another neural network is developed by [31] to recognize 24 hand gestures based on kinematic characteristics. The Euclidian distance is also available to detect the hand gesture based on Hu invariants of hand and area [2], eccentricity and solidity of hand gesture image[1].

Furthermore, a neural network produced a high accuracy of approximately 99% in detecting gestures [31]. In Table 8, we compare our proposed method with the other. As seen in Table 8, our proposed method has acceptable performance compared to other methods. Based on a review study [47], the hand gesture recognition accuracy ranges from 48% to 97%. With 99%, it shows the accuracy of the Naïve Bayes approach is higher than the other methods. This indicates that the proposed method has great potential for application. The developed method is also suitable for patients who need to rest their hands on the wheelchair's armrest or have difficulty lifting their shoulders and elbows because of their disability. The designed hand gestures are simple movements that are easily remembered and formed to make the user comfortable.

Human robot interaction is the main goal of developing the hand gesture recognition [12]. So, the qualitative testing of the proposed system was conducted to test the wheelchair. Figure 14(a) illustrates the user operating the wheelchair while the right hand performs the normal gesture for the stop command and Fig. 14(b) shows the trajectories (the blue arrow) used by the participants for trying out the wheelchair control using hand gestures based on naïve Bayesian. The experiment was started from the first trajectory and finished at the third trajectory. Responses from the participants were recorded and shown in Table 9.

Six participants were involved in the qualitative testing. Before conducting the test, one chance was provided to each participant, to freely attempt the wheelchair. The performances for the first attempt were recorded as the training session and the testing session was conducted after the user passed the training session.

The smoothness in controlling the machine was determined by the participant's ability to navigate the system from the first to the third trajectories. The assessment was used for testing the controllability of the wheelchair. The user was declared successful if the wheelchair could reach the last desired position. Furthermore, the participants were instructed to report their experiences, especially on the issue of fatigue. The result showed that all participants were able to finish the test, with none hitting the wall or moving in the wrong direction. The developed method shows satisfactory results in terms of controllability. The results also indicate that users are comfortable in operating the wheelchair.

V. CONCLUSION

A wheelchair is one of the important tools for people with special needs. A conventional wheelchair, however, can cause dilemma for users with finger problems. An alternative method to control wheelchairs is required to improve access of disabled patients, with an indirect control method is one of the options for controlling the wheelchair.

In this paper, a wheelchair controlled using wrist movement /wrist rotation was developed, with the pitch, yaw, and roll variables were used as the input features. As the stop command in operating the machine, the normal hand position was studied and selected to reduce muscle fatigue and maintain the system accuracy. Two gesture recognition algorithms were developed: threshold-based and Naïve Bayes-based approaches. Experiments showed that the Naïve Bayes is better than the threshold-based algorithm, classifying five forward, backward, left, and right gestures with 99% accuracy and precision. The proposed system has better and comparable results in comparison with others found in the literature. From qualitative testing, it was found that the proposed system was comfortable to be used.

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