A MACHINE-LEARNING-BASED FINGERTIP RECOGNITION TOWARDS ASSISTING HAND REHABILITATION

BY

DAYANG QURRATU'AINI BINTI AWANG ZA'ABA

A thesis submitted in fulfilment of the requirement for the degree of Master of Science (Mechatronics Engineering)

Kulliyyah of Engineering
International Islamic University Malaysia

SEPTEMBER 2020

ABSTRACT

For human beings, hands play a very important role in performing normal daily tasks. Therefore, when a person loses his/her hand's functionality, completely or partially, because of suffering from stroke for example, treatment to regain their motor skills is crucial. One of the widely practiced is by asking the patient to squeeze a flexible therapy ball in his/her hands repetitively. This post-stroke hand rehabilitation helps patients to improve dexterity, strength and fine motor skills that have deteriorated after a stroke. In order to improve the effectiveness of the therapy, the ability to measure objectively the progress that has been made without having to make any contact is deemed to be beneficial. The first step for achieving this is the ability to recognize the fingertips, which has been the aim of this work. This research developed algorithms that allow to recognize fingertips using commercial webcams and machine learning approach when a hand is holding a therapy ball. Two proposed methods were considered using the idea of extracting features from the image and use a trained classifier to identify the object of interest. The first algorithm is using Histogram of Oriented Gradient (HOG) as feature extractor and Support Vector Machine (SVM) as classifiers while the second algorithm is using Bag-of-Features (BoF) as a feature extractor and SVM as a classifier. Feature extractors like HOG and BoF extracts distinctive features from the input image and uses the information to train the SVM classifier. The trained SVM produces a classifier that distinguishes whether the feature belongs to a fingertip or not. Our results show that the success rates for the second method has an accuracy of 96% which is higher than the first algorithm that has an accuracy of 77%. This demonstrates that both BoF and SVM are promising techniques for the recognition of fingertip in therapy-ball-holding hands.

خلاصة البحث

بالنسبة للبشر ، تلعب اليدين دورًا مهمًا جدًا في أداء المهام اليومية العادية. لذلك ، عندما يفقد الشخص وظائف يديه ، كليًا أو جزئيًا ، بسبب المعاناة من السكتة الدماغية على سبيل المثال ، يكون العلاج لاستعادة مهاراته الحركية أمرًا بالغ الأهمية. أحد الممارسات الشائعة هو مطالبة المريض بالضغط على كرة علاج مرنة في يديه بشكل متكرر. يساعد هذا التأهيل اليدوي بعد السكتة الدماغية المرضى على تحسين البراعة والقوة والمهارات الحركية الدقيقة التي تدهورت بعد السكتة الدماغية. من أجل تحسين كفاءة العلاج ، تعتبر القدرة على القياس الموضوعي للتقدم الذي تم إحرازه دون الحاجة إلى إجراء أي اتصال مفيدًا. الخطوة الأولى لتحقيق ذلك هي القدرة على التعرف على أطراف الأصابع ، التي هي الهدف من هذا العمل. طور هذا البحث خوارزميات تسمح بالتعرف على أطراف الأصابع باستخدام كاميرات الويب التجارية ونهج التعلم الآلي عندما تمسك اليد كرة علاجية. تم النظر في طريقتين مقترحتين باستخدام فكرة استخراج المميزات من الصورة واستخدام التصنيف المدرب لتحديد الهدف محل الاهتمام. الخوارزميه الأولى تستخدم طريقه HOG لإستخراج المميزات و SVM للتصنيف بينما الخوارزميه الثانيه تستخدم طريقه BOF لإستخراج المميزات و SVM للتصنيف. تقوم مستخرجات الميزات متل HOG و BOF بإستخراج الميزات المختلفة من الصور المدخله وتستخدم المعلومات لتدريب المصنف SVM. المتدرب SVM ينتج مصنف يمكنه التمييز إذا كانت الميزة تنتمى إلى طرف الأصبع أم لا. تظهر نتأجنا أن معدلات النجاج للطريقه التانيه لها دقه تبلغ ٩٦٪ وهى أعلى من الطريقه الأولى التى تبلغ دقتها ٧٧٪. هذا يدل على أن BOF و SVM من التقنيات الواعدة للتعرف على أطراف الأصابع فى العلاج باستخدام إمساك الكرة بالأيدى.

APPROVAL PAGE

I certify that I have supervised and read this study and that in my opinion, it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a thesis for the degree of Master of Science (Mechatronics Engineering)

……..
Ali Sophian
Supervisor

……..
Hazlina Md. Yusof
Co-Supervisor

……..
Wahju Sediono
Co-Supervisor

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a thesis for the degree of Master of Science (Mechatronics Engineering)

……..
Muhammad Mahbubur Rashid
Internal Examiner

……..
Shazmin Aniza Abdul Shukor
External Examiner

This thesis was submitted to the Department of Mechatronics Engineering and is accepted as a fulfilment of the requirement for the degree of Master of Science (Mechatronics Engineering)

……..
Syamsul Bahrin Abdul Hamid
Head, Department of
Mechatronics Engineering

This thesis was submitted to the Kulliyyah of Engineering and is accepted as a fulfilment of the requirement for the degree of Master of Science (Mechatronics Engineering)

…….
Sany Izan Ihsan
Dean, Kulliyyah of Engineering

DECLARATION

I hereby declare that this thesis is the result of my own investigations, except where otherwise stated. I also declare that it has not been previously or concurrently submitted for any other degrees at IIUM or other institutions.

Dayang Qurratu'aini binti Awang Za'aba

Signature ..... Date .....

INTERNATIONAL ISLAMIC UNIVERSITY MALAYSIA

DECLARATION OF COPYRIGHT AND AFFIRMATION OF FAIR USE OF UNPUBLISHED RESEARCH

A MACHINE-LEARNING-BASED FINGERTIP RECOGNITION TOWARDS ASSISTING HAND REHABILITATION

I declare that the copyright holders of this thesis are jointly owned by the student and IIUM.

By signing this form, I acknowledged that I have read and understand the IIUM Intellectual Property Right and Commercialization policy.

Affirmed by Dayang Qurratu'aini binti Awang Za'aba

……..…….. ……..

Signature Date

ACKNOWLEDGEMENTS

I am grateful to the Almighty Allah S.W.T. for the good health and wellbeing that were necessary to complete this thesis. Although, it has been tasking, His Mercies and Blessings on me ease the herculean task of completing this thesis

Firstly, I am blessed with the continuous support and encouragement from my parents, Awang Za'aba and Faridah Balquis, and my husband, Muhammad Fitri, in terms of financial, motivation and inspiration throughout the journey of my studies and through the process of researching and completing this thesis. They have granted me the gift of their unwavering belief in my ability to accomplish this goal: thank you for your support and patience.

I would like to express my sincere gratitude to my supervisors, Assoc. Prof. Dr. Ali Sophian, Asst. Prof. Dr. Wahju Sediono and Asst. Prof. Dr. Hazlina Md. Yusof, for their continuous support, patience, motivation, and immense knowledge. The door to their office was always open whenever I ran into a trouble spot or had a question about my research or writing. They have allowed this thesis to be my own work but steered me in the right the direction whenever they thought I needed it.

I wish to express my appreciation and thanks to those who, directly or indirectly, provided their time, effort, and support for this project. To my fellow members of Machine Vision Laboratory, thank you for all the moral support throughout my master's degree journey. To the members of my thesis committee, thank you for all the feedbacks that helped me to improve my thesis. This accomplishment would not have been possible without them.

TABLE OF CONTENTS

Abstract ii
Abstract in Arabic iii
Approval Page iv
Declaration v
Copyright Page vi
Acknowledgements vii
Table of Contents viii
List of Tables xi
List of Figures xii
List of Abbreviations xiv

CHAPTER ONE: INTRODUCTION 1
1.1 Background of the Study 1
1.2 Problem Statement and its Significance 3
1.3 Research Objectives 3
1.4 Research Methodology 4
1.5 Research Scope 7
1.6 Thesis Outline 7

CHAPTER TWO: LITERATURE REVIEW 9
2.1 Introduction 9
2.2 Visual-based Fingertip Detection Approaches 10
2.3 Review of Machine Learning-Based Algorithm 20
2.4 Pre-processing 23
2.4.1 Color Spaces Conversion 23
2.4.1.1 RGB-Based Color Space (RGB, Normalized RGB) 24
2.4.1.2 Hue-Based Color Space (HSV, HSI, HSL) 25
2.4.1.3 Luminance-Based Color Space 27
2.4.1.4 CIE-Based Color Space (CIELUV, CIELAB) 29
2.4.2 Enhancement Operation 29
2.4.2.1 Median Filtering 30
2.4.2.2 Averaging Filtering 30
2.4.2.3 Otsu's Thresholding Method 31
2.4.2.4 Histogram Equalization 32
2.4.2.5 Morphological Operation 34
2.4.3 Summary of Pre-processing 35
2.5 Feature Extraction 37
2.5.1 Geometric Feature 37
2.5.2 SIFT 38
2.5.2.1 Scale-Space Extrema Detection 38
2.5.2.2 Keypoint Localization 39
2.5.2.3 Orientation Assignment 40
2.5.2.4 Description Generation 40
2.5.3 HOG Feature 41
2.5.4 Haar-like Feature 41

2.5.5 Summary of Feature Extraction 42
2.6 Classification 43
2.6.1 Support Vector Machine Classifier 43
2.6.2 AdaBoost Classifier 45
2.6.3 RDF Classifier 46
2.6.4 Summary of Classification 46
2.7 Chapter Summary 47

CHAPTER THREE: DEVELOPMENT OF FINGERTIP DETECTION ALGORITHM 49
3.1 Introduction 49
3.2 Test Rig Design 51
3.3 Image Datasets 52
3.4 Overview of Fingertip Recognition Algorithms 56
3.5 Algorithm 1: Histogram of Oriented Gradients and Support Vector Machine 57
3.5.1 Feature Extraction Using HOG 58
3.5.2 Classification Using SVM Classifier 59
3.6 Algorithm 2: Bag-of-Features and Support Vector Machine 61
3.6.1 Classifier Training Using Bag-of-Features 63
3.6.2 Classification Using SVM Classifier 65
3.7 Performance evaluation of machine learning algorithm 66
3.8 Chapter Summary 69

CHAPTER FOUR: EXPERIMENTAL RESULTS AND DISCUSSION 71
4.1 Introduction 71
4.2 Experimental Results for HOG and SVM Algorithm 72
4.2.1 Tuning HOG Parameter 72
4.2.2 Evaluation of Training and Testing Datasets on Recognition Accuracy 74
4.3 Experimental Results for BoF and SVM Algorithm 76
4.3.1 Preparation of Classifiers Using Training and Validation Image Set 76
4.3.2 Visual Vocabulary Development 78
4.4 Performance Analysis Based on Confusion Matrix 81
4.4.1 Results for HOG and SVM Algorithm 81
4.4.2 Results for BoF and SVM Algorithm 83
4.5 Performance Comparison 85
4.6 Chapter Summary 87

CHAPTER FIVE: CONCLUSION AND RECOMMENDATION 88
5.1 Conclusion 88
5.2 Recommendations 90

REFERENCES 92

LIST OF PUBLICATIONS 99

APPENDIX A: HOG AND SVM CODE 100

APPENDIX B: CLASSIFICATION TRAINING USING BOF 102

APPENDIX C: CLASSIFIER TESTING CODE 103

APPENDIX D: FINDING FINGERTIP CODE.....105

LIST OF TABLES

Table 2.1	A literature survey on methods for fingertip detection	13
Table 2.2	Summary of Image Pre-processing Techniques	36
Table 2.3	Summary of Feature Extraction Techniques	42
Table 2.4	Summary of Supervised Learning Classification Approaches	47
Table 3.1	Dataset images of hand and cropped fingertip images	54
Table 3.2	Table Representation of Confusion Matrix	66
Table 3.3	Table of terms that are associated with Confusion Matrix	67
Table 4.1	HOG parameter setup and detection accuracy of fingertip and non-fingertip images	72
Table 4.2	Training and testing dataset details	74
Table 4.3	Results of classifier training with a randomized input of training set, validation set and unused set	77
Table 4.4	Result of histogram and fingertip recognition in image based on different classfiers	79
Table 4.5	Results of confusion matrix and performance analysis for HOG and SVM algorithm	82
Table 4.6	Results of confusion matrix and performance analysis for BoF and SVM algorithm	84
Table 4.7	Overall comparison of HOG and SVM algorithm with BoF and SVM algorithm	87

LIST OF FIGURES

Figure 1.1	The flowchart of research methodology (x = presence of illumination)	6
Figure 2.1	General steps for fingertip detection	11
Figure 2.2	The process of supervised machine learning (Kotsiantis, 2007)	21
Figure 2.3	Machine Learning Phases	22
Figure 2.4	Example of color conversion from RGB color space to HSV color space	26
Figure 2.5	The separated color planes of an HSV Image	26
Figure 2.6	Application of Otsu's method on a fingertip image (a) gray image, (b) binary image (Image source: (Ling et al., 2016))	32
Figure 2.7	Illustration of Histogram Equalization: (a) input image, (b) histogram of the output image, (c) output image by the histogram equalization method, (d) histogram of the output image (Image source from (Singh & Dixit, 2015))	33
Figure 2.8	SIFT Descriptor Generation (Panchal et al., 2013)	41
Figure 3.1	Development process of machine learning based fingertip recognition	49
Figure 3.2	Experimental setup (Blue circles denoted the position of the hands used in experiment)	52
Figure 3.3	Methodology of data collection	55
Figure 3.4	Basic procedure for HOG and SVM algorithm	57
Figure 3.5	Histogram arrangement in HOG feature vector	59
Figure 3.6	Flowchart of algorithm	60
Figure 3.7	Overall process for BoF and SVM Algorithm	62
Figure 3.8	Training stage model	64
Figure 3.9	Validation stage model	65
Figure 4.1	A graph of the size of the cell vs accuracy of the detection of fingertip and non-fingertip	73

Figure 4.2 Outcome of the detection accuracy and number of training data 75

Figure 4.3 Results of best 4 classifiers in accuracy, precision, recall, specificity, and F1 score for HOG and SVM algorithm 82

Figure 4.4 Results of best 4 classifiers in accuracy, precision, recall, specificity, and F1 score for BoF and SVM algorithm 84

Figure 4.5 Performance comparison between HOG and SVM algorithm with BoF and SVM algorithm 86

LIST OF ABBREVIATIONS

ANN	Artificial Neural Network
BLOB	Binary Linked Object
BoF	Bag-of-Features
CB	Codebook
CCNM	Consecutive Count of Non-Movement
DSB-MM	Depth-Skin-Background Mixture Model
FPGA	Filed Programming Gate Array
GMM	Gaussian Mixture Model
GSP	Geodesic shortest path
HOG	Histogram of Orientation Gradient
ISO	International Organization for Standardization
LBP	Local Binary Patterns
LDDP	Local Depth Difference Pattern
PBH	Pixel-based Hierarchical
RDF	Random Decision Forest
RGB	Red, Green, Blue
ROI	Region of Interest
SIFT	Scale Invariant Feature Transform
SoG	Sum of Gaussians

CHAPTER ONE

INTRODUCTION

1.1 BACKGROUND OF THE STUDY

One of the most important aspect for independence in any individual's life is a normal working hands and fingers. Humans are indeed depended on a fully functioning hands and fingers which is an essential tool of the body to perform most of daily tasks until they are hindered in some way. Individuals who have experienced trauma of the hand or fingers require to rehabilitate the hand through physical therapy. One of the common conditions that can result the loss of hand functionality is stroke. Stroke is emerging as a major health problem and currently the third largest cause of death in Malaysia according to National Stroke Association of Malaysia (NASAM). The rate of incidence and prevalence of acute stroke in Malaysia increased dramatically for the past five years (Loo, K., 2012). The University of Malaya Medical Centre's senior consultant neurologist and stroke specialist says that globally, about 8-15 percent of stroke cases occur at the age below 45 and the frequency of stroke in young adults was observed to be rising in the region (Mustapha, 2015). The outcome of the present study on acute stroke in Malaysia will be notably contribute to the global stroke epidemiological data. Likewise, stroke remains as global leading cause of mortality especially in Malaysia (Loo, K., 2012).

Many stroke survivors have impaired hand function which limits the ability to perform tasks in normal daily life. Therefore, hand rehabilitation is crucial for the individual to regain back their motor skills of the affected hand. In many cases, there is an enormous potential for the brain to recover. Many physical therapies involve high repetitive and task-specific training in a motivating environment with active contribution of the individual is important for optimal motor relearning. One of the widely practiced is by asking the individual to squeeze a flexible exercise ball in his/her hands repetitively (Jaber; R.; Hewson; F., D.; J., 2012). The balls have various levels of resistance to accommodate the various levels of limitation of the patients' hands. However, it is currently not easy to monitor the effectiveness of the rehabilitation exercise without making any contact to their hand and causing extra loading to the arm/hand.

Based on many other research work done by other researchers, there are various ways to monitor the effectiveness of the rehabilitation exercise. However, most techniques are intrusive, i.e. the sensors and the system make contacts to the patient both directly or indirectly through other components (Mohan, Devasahayam, Tharion, & George, 2013). This will cause additional physical load to the associated arm or hand of the patient. In addition to that, prior preparation of the system is needed which adds extra time before the rehabilitation session. This can affect the psychological state of the patient negatively which may discourage the patient for performing the therapy. Therefore, this research work aims to develop a fingertip recognition algorithm to recognize fingertip in a single frame that contains a hand holding a therapy ball.

1.2 PROBLEM STATEMENT AND ITS SIGNIFICANCE

The existing approach for determining the position of fingertip are mostly intrusive whereby the system is required to have contact to the patient directly and indirectly. Unfortunately, this approach will require preparation time prior to the usage of the system and will cause unnecessary additional load to the affected hand which will lead to reliability issues and can affect the patient's emotional state negatively. Furthermore, the quantitative progress evaluation of fingertip during the rehabilitation is currently not available. Therefore, such a therapy can be benefited from contactless position measurement of the fingertips requires an effective recognition system. The partially occluded hand and the closed (non-extended) postures of the fingers make the problem particularly challenging, especially when a machine-learning-based method is adopted. Additionally, the complexity of the system can be influenced by different lighting conditions, the similarity in the color of the balls and the hands and the position of fingertips when they are close together.

1.3 RESEARCH OBJECTIVES

This work is aimed at recognizing fingertips from the hand that is holding a therapy ball and the objectives can be listed as follows:

1. To design and develop a test rig that allows single camera to be used for capturing pictures of a hand holding the therapy ball
2. To develop a machine learning-based algorithm for fingertip recognition for therapy-ball-holding hands
3. To evaluate the effectiveness of the recognition algorithm

1.4 RESEARCH METHODOLOGY

A comprehensive procedure of the research is divided into several stages, which includes literature survey on the several related works on the research, determination of machine vision hardware, development of test rig, image data collection and analysis, development of proposed algorithm, evaluation on the performance of the algorithm and discussion of the outcome obtained, and a conclusion is drawn in the end of the thesis.

i. Literature survey of technical and scientific papers

   The literature research was done to obtain the technical and scientific information related to the research. Resources are utilized from IIUM Library and online libraries such as IEEE Explore, ProQuest Dissertations and Theses Global, ScienceDirect, and Scopus. Furthermore, discussion and brainstorming amongst the researchers with the same field of interest were done as well.

ii. Determination of machine vision hardware

   Potential machine vision hardware included commercial webcams, Microsoft Kinect, Leap Motion controllers, and Time-of-flight cameras. The hardware selected for the project was a commercial webcam with an autofocus feature and a high resolution to capture photos.

iii. Design and development of test rig

   The test rig was used to collect data that allow different distances between the object, orientation of the hands, and the cameras and different lighting of illumination conditions.

iv. Image data collection and analysis

The database collection was done by capturing images of hands holding therapy balls. The collection covers different skin colors and hand orientation of the hand. Further analysis of the images collected was done using MATLAB 2016a software.

v. Development of fingertip recognition algorithm

Hand feature mainly the fingertip was identified and extracted for further processing. The algorithm was developed that implemented machine learning techniques. MATLAB and image processing toolbox were the main tool for algorithm development.

vi. Evaluation of the performance of the developed algorithm

The performance of developed algorithm was evaluated further by using the image collection gathered during the previous stage.

vii. Thesis writing

viii. Thesis submission

Figure 1.1 shows the flowchart of the research methodology including the research objectives.

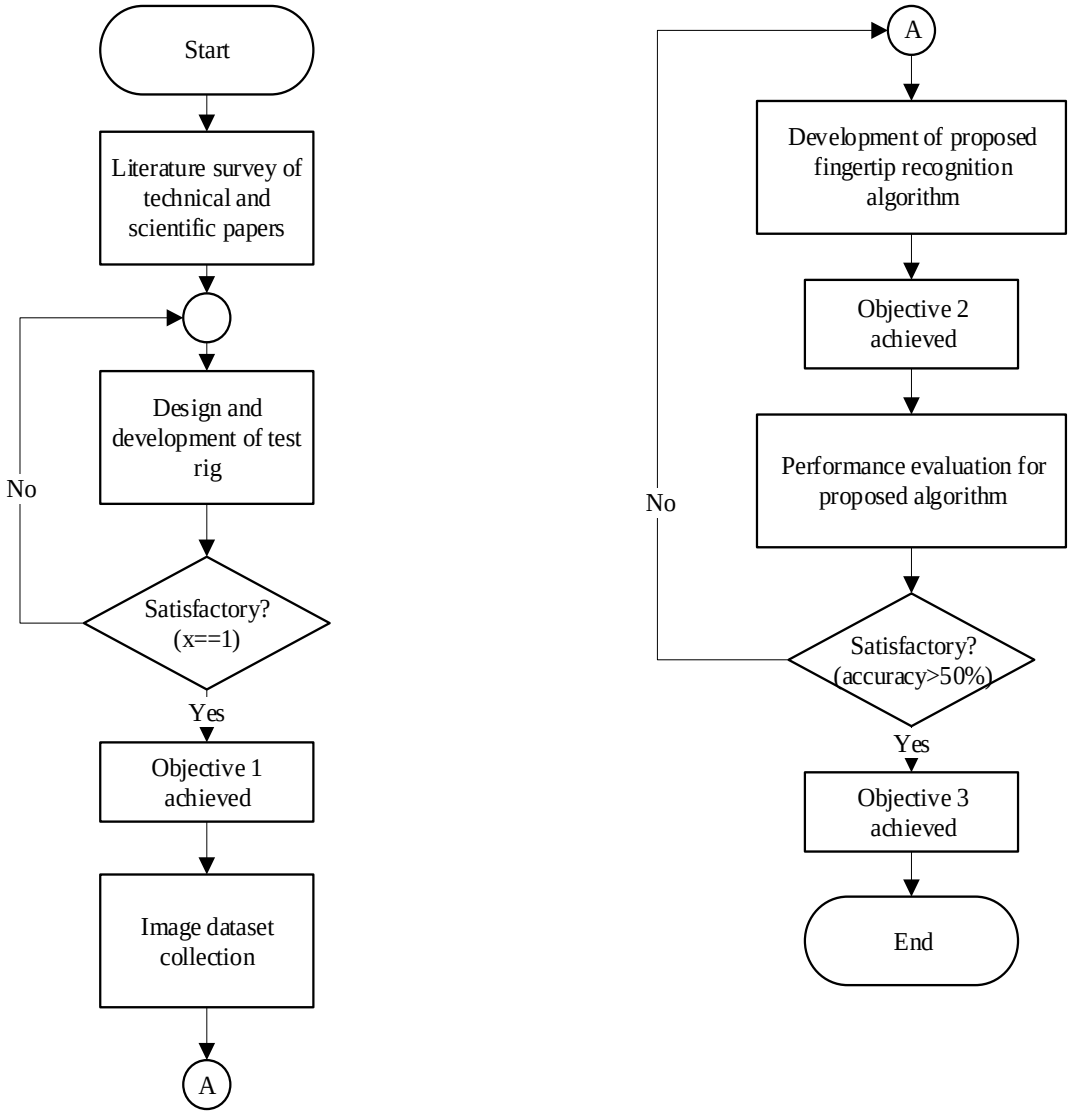

Figure 1.1 The flowchart of research methodology (x = presence of illumination)

1.5 RESEARCH SCOPE

In many applications of fingertip recognition used extended fingers with no interaction with any object within the hand region. There were no extra factors, like illumination and occluded hand, that can contribute the difficulty in recognizing fingertips. Most research work deals with extended fingers and no interaction with an object in the hand region. However, this research did not intend to cover those all those issues at once. The adopted machine learning algorithm for this research was based on the successful recognition rate in different applications. The dataset that was used throughout the research work deals with Asian skin tone primarily.

1.6 THESIS OUTLINE

This thesis compiles the research work on the machine learning-based fingertip recognition algorithm that can potentially be used in assisting hand rehabilitation.

Chapter 1 covers the introduction provides the background of fingertip recognition system, hand rehabilitation application, research related terms, problem statement of the research, objectives of the research, research methodology and describe the limitation of the research.

Chapter 2 reviews on detailed literature survey on the methods used in machine learning algorithm, pre-processing techniques, feature extraction and classification.

Chapter 3 describes the stages adopted in the proposed research methodology in this research. This chapter also explains briefly on the selected techniques in the algorithm.

Chapter 4 presents the outcome of the findings from the proposed method. The results are analyzed to evaluate the performance of the proposed algorithm. Some of the metrics used for performance evaluation are explained further in this chapter.

Lastly, Chapter 5 concludes the summary of the research contributions and recommendations on this research for future work.

CHAPTER TWO

LITERATURE REVIEW

2.1 INTRODUCTION

Stroke is widely known as leading cause of mortality globally, and this includes Malaysia (Loo, K., 2012). Many stroke survivors have impaired hand functionality which limits its ability to perform tasks in normal daily life. Therefore, hand rehabilitation is crucial for stroke patients to regain motoric skills of their affected hand. Many physical therapy interventions involving highly repetitive and task-specific training in a motivating environment with active contribution of the patient are important for optimal motor relearning. One of the widely practiced therapy is by asking the patient to squeeze a flexible exercise ball in his/her hands repetitively (Jaber; R.; Hewson; F., D.; J., 2012). The balls have various levels of resistance to accommodate the different levels of limitation of the patients' hands. However, one of the challenges is to measure quantitatively the progress that has been made. Therefore, position measurement of fingertips will be beneficial for implementing this measurement.

There are different ways proposed by researchers for measurement of finger's flexion and extension that can be used for rehabilitation therapy. However, most techniques are intrusive, i.e. the sensors and the system have to make contacts to the patient through other components (Mohan et al., 2013). This will cause additional physical load to the associated hand of the patient and will also be more likely to have

reliability issues. They will also require more time for preparation prior to the usage of the system and their obvious presence may also negatively affect the patient psychologically. Therefore, such approaches may discourage the patient for performing the therapy that they need.

Another approach that has machine-vision-based systems may offer a non-intrusive measurement of fingertip position. Some present rehabilitation is assisted by machine vision-based system involves the interaction between human and virtual world. Detection of fingertip are essential in the contactless position measurement. However, to have a good detection system, there are many challenges that need to be dealt with.

2.2 VISUAL-BASED FINGERTIP DETECTION APPROACHES

Various visual-based fingertip detection techniques have been studied and proposed by many researchers for different applications. Visual-based system incorporates camera hardware and computer vision algorithms to track the fingertips efficiently. This approach works at its best in controlled environment that has limited variables such as lighting level, skin tone color, and restricted background clutter. These are some of the external factors that affects the input source to the algorithm. A good hardware is important that would produce a relatively good image quality since the image captured will be inserted into the algorithm for further processing. Other types of surrounding factor that would influence the detection algorithm are sharpness, illumination, noise, sensitivity and ISO exposure, uniformity, distortion, and texture detail. Based on the literature survey, the stages for fingertip detection is generalized into 3 main stages