

# Table of Contents

Resumen.....	i
Abstract .....	ii
Publications.....	v
List of Tables .....	xi
List of Figures.....	xii
List of Acronyms .....	xiv
<b>1 Introduction</b> .....	<b>1</b>
1.1 Motivation .....	1
1.2 Justification .....	2
1.3 Problem Statement .....	4
1.4 Objectives.....	5
1.5 Models.....	5
1.6 Methodology .....	7
1.7 Thesis Structure.....	9
<b>2 Related Work</b> .....	<b>10</b>
2.1 Natural User Interfaces.....	10
2.1.1 Examples of Application Domains .....	11
2.2 Gestures .....	12
2.2.1. Understanding Gestures .....	13
2.2.2. Enabling Technologies for Acquisition .....	16
2.2.3. Design Aspects.....	17
2.3 Model-Based Evaluation .....	20
2.3.1 Descriptive Models.....	20
2.3.2 Predictive Models .....	21
2.3.3 Model Validity .....	26
<b>3 Observing Users Performing Gestures</b> .....	<b>27</b>
3.1 User Study .....	27
3.1.1 Participants.....	28
3.1.2 Apparatus .....	28
3.1.3 Procedure and tasks.....	28
3.2 Open-Ended Task Results .....	29
3.2.1 General Observations.....	30

3.2.2	GCP: A Model on Gestures Conception and Production.....	30
3.2.3	A Taxonomy of Touchless Gestures.....	32
3.3	Goal-Oriented Task Results .....	33
3.3.1	Gesture variations .....	33
3.3.2	Physicality Breakdown .....	35
3.3.3	Movement Breakdown.....	37
3.3.4	Structure Breakdown .....	38
3.3.5	Mental Model Observations.....	39
3.4	Discussion and Design Implications .....	40
3.4.1	Touchless Gesture Ergonomics.....	41
3.4.2	Touchless Gesture Design.....	42
3.4.3	Touchless Gesture Recognizers .....	42
3.5	Conclusions .....	42
<b>4</b>	<b>Estimating Production Time of Touchless Hand Drawing Gestures</b>	<b>44</b>
4.1	Candidate Models.....	45
4.2	Hypotheses and Research Design.....	46
4.2.1	Apparatus and Method.....	47
4.3	Definition of Formulas .....	49
4.3.1	CLC Model .....	49
4.3.2	Isokoski's Model.....	49
4.3.3	KLM.....	50
4.4	Estimation of Parameters.....	50
4.4.1	CLC Model .....	50
4.4.2	Isokoski's Model.....	53
4.4.3	KLM.....	53
4.5	Evaluation of Models .....	55
4.5.1	CLC Model .....	55
4.5.2	Isokoski's Model.....	56
4.5.3	KLM.....	57
4.6	General Comparison.....	58
4.7	Discussion .....	59
4.8	Conclusions .....	60
<b>5</b>	<b>Predicting Task Execution Times</b>	<b>62</b>
5.1	Touchless Hand Gesture Level Model (THGLM) .....	63
5.1.1	Model Description .....	64
5.1.2	Definition of Model Operators.....	64
5.2	Finding Expressive Operators .....	66
5.2.1	Method .....	66
5.2.2	Results.....	68
5.3	User Study for Time Measurements.....	69
5.3.1	Method .....	69
5.3.2	Holding ( <i>H</i> ).....	70
5.3.3	Tapping ( <i>T</i> ) .....	71
5.3.4	Swipping ( <i>S</i> ).....	71
5.3.5	Gripping ( <i>G</i> ) and Releasing ( <i>R</i> ).....	71
5.3.6	Drawing ( <i>D</i> ).....	72
5.3.7	Preparation ( <i>Pr</i> ) and Retraction ( <i>Re</i> ) .....	72

5.3.8	Pointing ( <i>P</i> ).....	72
5.3.9	Mentally Prepare ( <i>M</i> ).....	73
5.4	Overview of THGLM Operators .....	73
5.5	Using THGLM .....	74
5.5.1	Including Mental Operators .....	74
5.5.2	A Procedure to Apply THGLM .....	75
5.5.3	Example .....	76
5.6	Discussion .....	77
5.7	Conclusions .....	79
<b>6</b>	<b>Validation of the Model</b> .....	<b>80</b>
6.1	Empirical Validation .....	80
6.1.1	Method .....	81
6.1.2	Results.....	84
6.2	Using the Model to Analyze Interface Designs.....	85
6.2.1	Method .....	86
6.2.2	Results.....	87
6.3	Validation with Designers .....	87
6.3.1	Part 1: Model Predictions.....	88
6.3.2	Part 2: Observed Values.....	90
6.3.3	Results.....	90
6.3.4	Discussion.....	92
6.4	Conclusions .....	93
<b>7</b>	<b>Extending the Model</b> .....	<b>94</b>
7.1	Candidate Operators .....	94
7.1.1	Mentally Prepare.....	94
7.1.2	Hand Preference ( <i>Hp</i> ) .....	95
7.1.3	Other Stroke Operators .....	96
7.2	User Study for Time Measurements.....	96
7.2.1	Method .....	96
7.2.2	Results.....	99
7.3	Using the New Operators .....	100
7.4	Further Model Extensions .....	101
7.5	Conclusions .....	102
<b>8</b>	<b>Conclusions</b> .....	<b>103</b>
8.1	Extending Existing Models .....	103
8.2	Formulating a New Model .....	104
8.3	Validating the Model.....	105
8.4	Applying the Model.....	106
8.5	Contributions .....	107
8.6	Future Work .....	107
	<b>Appendices</b> .....	<b>109</b>
<b>A</b>	<b>Models for Touchless Hand Drawing Gestures (THDG)</b> .....	<b>109</b>
A.1	Applicability.....	109
A.2	Description .....	109

A.3	Limitations.....	110
<b>B</b>	<b>Touchless Hand Gesture Level Model (THGLM)</b>	<b>111</b>
B.1	Applicability.....	111
B.2	Description .....	111
B.3	Limitations.....	115
<b>C</b>	<b>Touchless Hand Gestures Commonly Used in NUIs</b>	<b>116</b>
<b>D</b>	<b>Questionnaires used for the Studies</b>	<b>117</b>
D.1	Example of Demographics Questionnaire.....	117
D.2	Questionnaire for the study in Section 6.3 .....	118
D.3	Questionnaire for the study in Chapter 7.....	120
	<b>Glossary</b>	<b>121</b>
	<b>Bibliography</b>	<b>123</b>
	<b>Additional Bibliography</b>	<b>133</b>

# List of Tables

2.1	Overview of KLM operators in relation to possible uses with THG .....	23
3.1	A taxonomy of touchless gestures.....	33
3.2	Friedman tests for gesture type on level types .....	36
4.1	Research design.....	46
4.2	Constant times for Isokoski’s model.....	53
4.3	Comparison of CLC model predictions .....	55
4.4	Comparison of the three models.....	58
4.5	Best version of each analyzed model ordered from best to worst.....	61
5.1	Search terms .....	67
5.2	Stroke operators.....	68
5.3	Overview of the proposed operators with the corresponding values .....	73
6.1	Participants’ characteristics by experiment.....	81
6.2	Summary of software characteristics by experiment .....	83
7.1	Overview of the proposed times for the new operators.....	99
A.1	Best version of each analyzed model ordered from best to worst.....	110
B.1	Final list of the proposed operators with the corresponding values .....	112
C.1	Touchless hand gestures commonly used in NUIs or touchless interaction .....	116

# List of Figures

1.1	System and model .....	6
1.2	Structure of the thesis .....	7
2.1	Application example of NUIs.....	11
2.2	Example of gestures used in this thesis decomposed in phases .....	12
2.3	G-units, g-phrases and phases .....	13
2.4	Main components of (a) Kinect and (b) Leap Motion.....	17
2.5	Gesture space.....	18
2.6	User representation.....	19
2.7	Fitts' law.....	24
3.1	The set of 20 gesture types used in the experiment.....	29
3.2	GCP, a model on user conception and production of touchless gestures.....	31
3.3	Number of variations for each gesture type .....	34
3.4	Various articulation patterns for the “X” symbol produced with several poses .....	34
3.5	Gesture physicality ratio.....	35
3.6	Upper limb ratios according to spatial relation .....	36
3.7	Gesture movement composition ratio.....	37
3.8	Gesture structure ratio .....	38
3.9	Gesture structure ratio by used effectors .....	39
4.1	Interface of the experimental software.....	48
4.2	Straight line production time .....	51
4.3	Curve production time.....	52
4.4	Net corner time contribution .....	53
4.5	Gestures used in experiment E2 .....	54
4.6	Comparison of observed and predicted times of 4 gestures .....	54
4.7	CLC model prediction .....	56
4.8	Comparison of Isokoski's model prediction errors .....	56
4.9	Isokoski's model prediction .....	56
4.10	Comparison of observed and predicted times using both CLC and Isokoski's models ..	57
4.11	Gestures used in E3 .....	57
4.12	Comparison of observed and predicted times for experiment E3 .....	58
4.13	General comparison of observed and predicted times using CLC, Isokoski's and KLM models .....	59

5.1	Literature review results .....	68
5.2	Interface of the experimental software .....	70
5.3	Gesture set used for drawing task.....	72
5.4	Set of updated heuristics for placing M operators.....	74
5.5	Procedure to apply THGLM.....	76
5.6	Example of using THGLM.....	77
6.1	Applications used in the experiments.....	82
6.2	Task execution times .....	85
6.3	THGLM prediction.....	85
6.4	Design options used in the study .....	86
6.5	Observed and predicted times for the three design options.....	87
6.6	User interface utilized in the study .....	89
6.7	Comparison of observed times and times predicted by a researcher and designers.....	91
6.8	Designers' opinions about the procedure to apply THGLM .....	92
7.1	Comparison of current and previous times for three operators .....	100
A.1	Gesture “D” and “E” represented with straight lines .....	110
B.1	G-units, g-phrases and phases in the context of THGLM .....	111

# List of Acronyms

CLC	Curves, Line segments, and Corners
DH	Dominant hand
FPS	Frames per second
GCP	(A model on) Gestures Conception and Production
G-phrase	Gesture phrase
G-unit	Gesture unit
HCI	Human Computer Interaction
KLM	Keystroke-Level Model
LM	Leap Motion
MT	Movement time
NDH	Non-dominant hand
NUI	Natural User Interface
OP	Operator
RGB	Red, green and blue
RMSE	Root mean square error
RT	Reaction time
SD	Standard deviation
SDK	Software development kit
ST	Stroke time
TG	Touchless Gestures
THDG	Touchless Hand Drawing Gestures
THG	Touchless Hand Gestures
THGLM	Touchless Hand Gesture Level Model
UI	User Interface
WOz	Wizard of Oz