# CONTENTS

ABSTRACT (in Chinese) ........................................................................................................ i
ABSTRACT (in English) ........................................................................................................ ii
ACKNOWLEDGEMENTS ...................................................................................................... iv
CONTENTS .......................................................................................................................... v
LIST OF FIGURES ................................................................................................................ vii

<table>
<thead>
<tr>
<th>Chapter</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Introduction</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>1.1 Motivation</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>1.2 Survey of Related Studies</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>1.3 Overview of Proposed Approach</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>1.4 Contributions</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>1.5 Thesis Organization</td>
<td>8</td>
</tr>
<tr>
<td>2</td>
<td>System Configuration and Guidance Principles</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>2.1 Introduction</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>2.2 System Configuration</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>2.2.1 Hardware configuration</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>2.2.2 Software configuration</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>2.3 Learning Strategy Principle and Major Steps in Proposed Process</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>2.4 Human Detection Principle and Major Steps in Proposed Process</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>2.5 Human Following Principle and Major Steps in Proposed Process</td>
<td>22</td>
</tr>
<tr>
<td></td>
<td>2.6 Human Interaction Principle and Major Steps in Proposed Process</td>
<td>23</td>
</tr>
<tr>
<td>3</td>
<td>Camera Calibration for Distance Computation</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>3.1 Introduction</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>3.1.1 Coordinate Systems</td>
<td>26</td>
</tr>
<tr>
<td></td>
<td>3.1.2 Directional Angles of Camera</td>
<td>28</td>
</tr>
<tr>
<td></td>
<td>3.2 Review of Proposed Distance Computation Method</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>3.3 Adaptation to Different People’s Heights</td>
<td>33</td>
</tr>
<tr>
<td></td>
<td>3.3.1 Using reference data information</td>
<td>33</td>
</tr>
<tr>
<td></td>
<td>3.3.2 Changes of viewing distance</td>
<td>38</td>
</tr>
<tr>
<td></td>
<td>3.4 Area Tracking</td>
<td>41</td>
</tr>
<tr>
<td></td>
<td>3.4.1 Human clothes color extraction</td>
<td>41</td>
</tr>
<tr>
<td></td>
<td>3.4.2 Deciding area centers by a shape circumscribing method</td>
<td>43</td>
</tr>
<tr>
<td></td>
<td>3.4.3 Adjustment of Camera orientations for area monitoring</td>
<td>44</td>
</tr>
<tr>
<td>4</td>
<td>Human Detection Technique for Person Following</td>
<td>47</td>
</tr>
</tbody>
</table>
4.1 Introduction........................................................................................................ 47
4.2 Proposed Process of Human Detection............................................................ 48
4.3 Review of a Face Detection Method................................................................. 49
4.4 Adaptation to Changes of Luminance.............................................................. 50
  4.4.1 A Skin Detection Model............................................................................. 51
  4.4.2 Curve fitting.............................................................................................. 57
  4.4.3 Human detection by a progressive method.............................................. 62

Chapter 5 Human Following Techniques by Indoor Autonomous Vehicle.......... 67
  5.1 Introduction.................................................................................................... 67
  5.2 Proposed Process of Human Following....................................................... 68
  5.3 Fast Human Turning at A Corner in A Narrow Path................................. 70
    5.3.1 Adaptation to fast turning by crossroad points .................................... 71
    5.3.2 Recording direction of fast human disappearance by a vehicle arm ......... 73

Chapter 6 Human Interaction Techniques for Indoor Person Following.......... 80
  6.1 Introduction.................................................................................................. 80
  6.2 Human Facing Direction Detection ............................................................. 81
    6.2.1 Finding aspect ratios of human bodies............................................... 84
    6.2.2 Finding human face centers ................................................................. 85
    6.2.3 Experimental results............................................................................ 89
    6.2.4 Application as a tour guide ................................................................. 90
  6.3 Human Hand Movement Detection by Motion Analysis............................ 93
    6.3.1 Motion detection by frame differencing ............................................. 95
    6.3.2 Vehicle calling by combining the facing direction detection method ....... 96
    6.3.3 Experimental results.......................................................................... 97
    6.3.4 Application as a shopping cart......................................................... 98

Chapter 7 Experimental Results and Discussions......................................... 102
  7.1 Experimental Environment.......................................................................... 102
  7.2 Experimental Results.................................................................................. 103
  7.3 Discussions.................................................................................................. 110

Chapter 8 Conclusions and Suggestions for Future Works............................ 112
  8.1 Conclusions................................................................................................ 112
  8.2 Suggestions for Future Works................................................................... 114

References............................................................................................................ 116
LIST OF FIGURES

Figure 1.1 A flowchart of proposed system ................................................................. 7
Figure 2.1 Equipment connection situation in this study. ............................................... 11
Figure 2.2 The vehicle Pioneer3 used in this study. (a) A front view of the vehicle. (b) A side view of the vehicle. ................................................................. 12
Figure 2.3 The camera AXIS210 used in this study. (a) A front view of the camera. (b) A side view of the camera................................................................. 13
Figure 2.4 The light equipments used in this study. (a) Light stand with an EYE bulb off. (b) Light stand with the EYE bulb on......................................................... 14
Figure 2.5 Digital light meter. .......................................................................................... 15
Figure 2.6 An illustration of the learning strategy process to get the reference data. 16
Figure 2.7 An illustration of the learning strategy process for different people heights .................................................................................................................. 17
Figure 2.8 An illustration of the learning strategy process for a person making a fast turn. .................................................................................................................. 18
Figure 2.9 An illustration of the learning strategy process for the person following application ................................................................. 19
Figure 2.10 An illustration of the human detection process. ......................................... 21
Figure 2.11 An illustration of the human following process ........................................... 23
Figure 2.12 An illustration of the human interaction process ....................................... 24
Figure 3.1 The coordinate systems used in this study. (a) The image coordinate system. (b) The global coordinate system (c) The vehicle coordinate system. (d) The spherical coordinate system. ................................................................. 28
Figure 3.2 The pan angle of the camera. (a) \(0 \leq \theta_c \leq \pi\). (b) \(0 \geq \theta_c \geq -\pi\). .................................................................................. 29
Figure 3.3 The tilt angle of the camera. (a) \(0 \leq \phi_c \leq \frac{\pi}{2}\). (b) \(0 \geq \phi_c \geq -\frac{\pi}{2}\). .................................................................................. 29
Figure 3.4 Coordinate systems used (a) Image coordinate system. (b) Spherical coordinate system. .................................................................................................................. 31
Figure 3.5 Image coordinates mapped into real world space ........................................ 31
Figure 3.6 The illustration of the distance \(d\) between a person and the vehicle. .......... 32
Figure 3.7 Te reference data information ........................................................................ 35
Figure 3.8 Getting the reference data \(D_{refI}\). (a) Reference person standing in front of the vehicle. (b) The vehicle can see the whole clothes of the Reference person. .................................................................................. 35
Figure 3.9 (a) The distance \(D_{refI}\) for the reference person. (b) The new distance \(D_{newI}\) for another person.................................................................................................................. 40
Figure 3.10 Extraction of human clothes region .......................................................... 43
Figure 3.11 Deciding the area center ......................................................................... 44
Figure 3.12 (a) The person is too right to the vehicle. (b) The result of the adjustment. .......................................................... 46
Figure 4.1 An illustration of the human detection process ......................................... 49
Figure 4.2 The elliptic skin model ............................................................................ 50
Figure 4.3 An illustration of the positions of the equipment in the experiment ........... 54
Figure 4.4 Retrieved five skin parts in the face .......................................................... 54
Figure 4.5 The results of the experiment of building a skin detection model ............. 57
Figure 4.6 The distribution of results of $C_b$ and $C_r$ ............................................. 58
Figure 4.7 The results of line fitting of $C_b$. The intensity $Y$ is from (a)16~80 (b) 81~145 (c)146~234 .......................................................... 61
Figure 4.8 The results of line fitting of $C_r$. The intensity $Y$ is from (a)16~64 (b) 65~159 (c)160~234 .......................................................... 62
Figure 4.9 The detection of human face by the progressive method. (a) The block size is 320x240. (b) Skin color region of (a). (c)The block size is 160x120. (d) Skin color region of (c). (e) The block size is 80x60 and the face of the person is detected successfully. (f) Skin color region of (e) ........................................ 65
Figure 4.10 The detection of human face by progressive method. (a) The block size is 320x240. (b) Skin color region of (a). (c)The block size is 160x120. (d) Skin color region of (c). (e) The block size is 80x60 and detect the face of the person. (f) Skin color region of (e). (g) The block size is 40x30 and the face of the person is detected successfully. (h) Skin color region of (g) ............ 66
Figure 5.1 An illustration of the human following process ........................................... 69
Figure 5.2 An illustration of the turning mode ........................................................... 70
Figure 5.3 An illustration of the crossroads points ..................................................... 72
Figure 5.4 Choosing the correct crossroad point for searching the followed person. .... 73
Figure 5.5 The direction of the vehicle in the real world ........................................... 73
Figure 5.6 The original direction of the vehicle ........................................................... 74
Figure 5.7 An illustration of turning the robotic arm (a) The person is too right to the vehicle. (b) Adjust the degree of the arm ........................................... 75
Figure 5.8 Measure the side of the turning direction. (a) Right. (b) Left .................... 77
Figure 5.9 The direction of the vehicle (a) Case 1. (b) Right and left side of (a). (c) Case 2. (d) Right and left side of (c). (e) Case 3. (f) Right and left side of (e). (g) Case 4. (h) Right and left side of (g). (i) Case 5. (j) Right and left side of (j). ........................................ 79
Figure 5.10 Turn to the correct direction (a) Turn right with angle $\theta_r$. (b) Turn left with angle $\theta_l$ .......................................................... 79
Figure 6.1 A flowchart of human interaction...............................................................81
Figure 6.2 An illustration of detection of a person’s facing direction. ......................83
Figure 6.3 An illustration of the facing direction of the person. (a) Front. (b) Back. (c)
Left. (d) Right. ............................................................................................88
Figure 6.4 Some experimental results of facing direction detection. (a) Front. (b) Back.
(c) Right. (d) Left........................................................................................90
Figure 6.5 The process as a tour guide. .................................................................91
Figure 6.6 An illustration of area information. .........................................................92
Figure 6.7 An illustration of the vehicle being used as a tour guide.........................92
Figure 6.8 An illustration of detection of hand movement.......................................94
Figure 6.9 An experimental result of human hand movement detection. (a) The
detection of the facing direction in input images. (b) The result of the motion
detection......................................................................................................98
Figure 6.10 The process as a shopping cart. ............................................................99
Figure 6.11 The illustration of calling the vehicle as a shopping cart......................100
Figure 6.12 An experimental result of the vehicle being a cart in the library.........101
Figure 7.1 The illustration of the CV Lab in NCTU................................................102
Figure 7.2 The vehicle follows a person as a shopping cart.................................103
Figure 7.3 An interface of the experiment. The green box shows the image stream and
the blue box shows the input image at this moment. The yellow box shows
the difference image and the red box shows the output image.....................105
Figure 7.4 An experimental result of face detection and extraction of the clothes. (a)
The output image with a detected face region and the extracted clothes
region by region growing. (b) The image of the extracted clothes............105
Figure 7.5 An experimental result of the person turning fast at a corner. (a) The input
image. (b) The position of the vehicle..........................................................106
Figure 7.6 The vehicle makes an introduction about these books. (a) The facing
direction of the person is back and the media introduction is off. (b) The
person is facing some books and the media introduction is on.................107
Figure 7.7 An experimental result of detecting the person waving her hand. (a) The
input image. (b) The result of motion detection...........................................108
Figure 7.8 An illustration of the experimental process..........................................109
Figure 7.9 An illustration of the learned data and the actual path of following a person
in an experiment.......................................................................................110