UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

Using Catadioptrics for multidimensional interaction in Computer Graphics

by

James Lane

Submitted in partial fulfillment of the requirements for the degree of Magister Scientiae

in the Faculty of Natural Science

University of Pretoria

Pretoria

Republic of South Africa

November 2001

© University of Pretoria

Dedicated to my Lord Jesus Christ,
Who faithfully stood by me
And saw me through to the end

Thanks to Dad, Mom, John and Lona
Vali for her patience and invaluable help
Andrè Nel
Gerry and Robin for all their help and prayers
Frans, Jaques, Marde, Jeremy, Gernot, Jeurgen, Dr Eckles
and everybody from the
Virtual Environments group at GMD
and the University of Pretoria

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

Using Catadioptrics for multidimensional interaction in Computer Graphics

by

James Lane

Abstract

This thesis introduces the use of catadioptrics for multidimensional interaction in the approach called Reflections.

In computer graphics there is a need for multidimensional interaction that is not restricted by cabling connected to the input device. The use of a camera and computer vision presents a solution to the cabling problem. Unfortunately this solution presents an equally challenging problem: a single camera alone can not accurately calculate depth and is therefore not suitable for multidimensional interaction.

This thesis presents a solution, called reflections to this problem. Reflections makes use of only a single camera and one or more mirrors to accurately calculate 3D, 5D, and 6D information in real time.

Two applications in which this approach is used for natural, non-intrusive and multidimensional interaction are the Virtual Drums Project and Ndebele painting in virtual reality. The interaction in these applications and in particular the Virtual Drums is appropriate and intuitive, e.g. the user plays the drums with a real drumstick. Several computer vision algorithms are described in this thesis, which are used in the implementation of the Virtual Drums Project.

Thesis supervisor: Prof. V. Lalioti

Department of Computer Science

University of Pretoria

Submitted in partial fulfillment of the requirements for the degree of Magister Scientiae

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

Die gebruik van Katadioptika vir multidimensionele interaksie in Rekenaar Grafika

deur

James Lane

Opsomming

Hierdie tesis bied die gebruik aan van katadioptika vir multidimensionele interaksie in die metode wat Refleksie genoem word.

In rekenaar grafika is daar n behoefte aan multidimensionele interaksie wat nie beperk word deur kabels wat gekoppel is aan die invoer meganisme. Die gebruik van 'n kamera en rekenaarvisie is 'n oplossing vir hierdie probleem. Ongelukig presenteer hierdie oplossing 'n soortgelyke uitdagende probleem; 'n enkele kamera kan diepte nie akkuraat bereken nie en dit is daarom nie geskik vir multidimensionele interaksie nie. Daarom is die gebruik van n enkele kamera nie 'n geskikte oplosing vir multidimensionele interaksie nie.

Hierdie tesis stel n oplosing voor vir die probleem wat Refleksies genoem word. Refleksies maak gebruik van 'n enkele kamera en een of meer spieèls om 3D, 5D en 6D inligting akkuraat te bereken.

Twee toepassings waarin hierdie benadering gebruik word vir natuurlike nie indringende en multidimensionele interaksie, word in hierdie tesis aangebied, naamlik die Virtuele Dromme Projek en die Ndebele Skilderkuns in virtuele realiteit (VR). Die interaksie in hierdie toepassings en veral die Virtuele Dromme is gepas en intuitief, byvoorbeeld die gebruiker speel die dromme met 'n regte dromstok. Verskillende rekenaarvisie algoritmes

wat in die implementering van die Virtuele Dromme Projek gebruik word, word in hierdie tesis beskryf.

Studie leier: Prof. V. Lalioti
Department Rekenaarwetenskap
Universiteit van Pretoria

Voorgele ter gedeeltelike vervulling van die vereistes vir die graad Magister Scientiae

Contents

1 Introduction 1

1.1 Thesis Focus 2

1.2 Layout of the Work 2

2 Literature Study 4

2.1 Virtual Reality 5

2.1.1 Immersive Technologies 6

2.1.2 Stereo Vision 7

2.1.3 Display Systems 9

(a) Stereoscopic Monitors 10

(b) Workbenches 11

(c) Caves 11

2.1.4 Spatial Audio 13

2.1.5 Tracking 14

2.1.6 Sensory Technology for Tracking and Interaction 15

a) Contact Sensing Technologies 15

b) Non-contact Sensing Technologies 16

2.1.7 Interaction in VR 18

2.2 Interaction 19

2.2.1 Interaction Metaphors for Virtual Environments 20

2.2.2 Natural Interaction 21

2.2.3 Non-intrusive Interaction 24

2.2.4 Examples of Natural and Non-intrusive Interaction 25

2.3 Computer Vision 27

2.3.1 Overview 28

2.3.2 Colour, Light and Infrared 30

2.3.3 Meaningful Features 31
2.3.4 Tracking 33
2.3.5 The 2D to 3D Problem 35
(a) Single Camera Solutions 35
(b) Multiple Camera Solutions 36
2.4 Catadioptrics 37
2.5 Summary 39

3 Theory **41**

3.1 Reflections 42
3.1.1 Overview 42
3.1.2 Approach 46
3.1.3 Relative Orientation 48
3.1.4 Apparatus 49
(a) The Image Capture Device 49
(b) The Reflective Surfaces 50
(c) The Computer, the Tracked Object and Lighting 51
3.1.5 Image Formation 52
(a) Epipolar Geometry 53
(b) Rectified Catadioptric Stereo 54
3.1.6 Camera Mirror Setup 56
3.1.7 3D Calculation 58
(a) Physics 58
(i) Light 58
(ii) Mirrors 59
(iii) The Pinhole Camera Model 61
(b) Calibration 63
(i) Calculating the Focal Length and Angle of View 64
(ii) Assumptions and Setup 66
(c) The Mathematical Model 67
(d) The Pre-Processing Step 68

(e) From the Film Plane to the Real World 71
(f) Initial Calculations 73
(g) Geometric & Trigonometric Calculation 74
(h) Algebraic Alternative 76
3.1.8 5D/6D Calculation 78
3.2 Computer Vision 82
3.2.1 Colour & Inverse Chroma Keying 82
(a) Colour 83
(b) A Fast Chroma Keying Algorithm 85
3.2.2 Image Moments 86
3.2.3 Stereo Matching 88
3.2.4 SUSAN 90
(a) Edge Detection 92
(b) Corner Detection 95
3.3 Tracking 97
3.3.1 A Window Based Tracker 97
3.3.2 A Predictive Curve Tracker 98
3.3.3 Multiple Object Tracking 99
3.4 Summary 100

4 Reflections in Interactive Applications **102**

4.1 Design and Implementation 103
4.1.1 The Physical Installation Process 104
4.1.2 The Computational Process 106
4.2 Virtual Drums 108
4.2.1 The Application 108
(a) Visualization 108
(b) Sound 109
(c) Interaction 110
4.2.2 The Prototype 111
4.2.3 The AVANGO Implementation 113

(a) The Computer Vision and Tracking Algorithms 118
(b) The 5DOF Extension 123
(c) Tracking Multiple Drumsticks 125
4.3 Ndebele Paintings 126
4.3.1 The Existing Application 127
4.3.2 Ndebele Painting Meets Reflections 128
4.4 Development Platform 130
4.5 Implementing Reflections in Different Environments 130
4.5.1 Desktop 131
4.5.2 Responsive Workbench 131
4.5.3 CyberStage 132
4.6 Summary 132

5 Results **134**
5.1 Accuracy 135
5.1.1 Position 135
5.1.2 Angular Accuracy 137
5.1.3 Stability 140
5.1.4 Interaction Volume 142
5.2 Speed 142
5.3 Performance of the Computer Vision Algorithms 143
5.3.1 Efficiency of the Algorithms 143
5.3.2 Effectiveness of the Algorithms 148
5.4 Tracker Performance 150
5.5 Summary 155

6 Conclusions and Future Work **156**
6.1 Conclusions 157
6.2 Future Work 158

7 Bibliography 160

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

List of Figures

Figure 2.1 Pictures of Virtual Worlds 5
Figure 2.2 Binocular Disparity 8
Figure 2.3 A Picture of CyberStage 13
Figure 2.4 Elements of Interaction 20
Figure 2.5 Classes of Interaction for 3D User Interfaces 21
Figure 2.6 Effects of Natural Interaction 22
Figure 2.7 Illustration of a Pixel and a Frame and their Representation in Memory 28
Figure 2.8 Features Obtained During Image Analysis 29
Figure 2.9 Illustration of the 2D to 3D Problem 35
Figure 2.10 Catadioptric Stereo Sensor 38
Figure 3.1 Illustration of a Camera and Mirror Setup 43
Figure 3.2 Illustration of Region of Interaction 44
Figure 3.3 Illustration of Where the Image Analysis Phase Locates the Object and its Reflection in an Image 45
Figure 3.4 Views of a Camera and Mirror Setup 46
Figure 3.5 Geometry of Catadioptric Stereo 47
Figure 3.6 Relative Orientation 48
Figure 3.7 Picture Taken by Camera in a Simple Reflective Setup 53
Figure 3.8 Epipolar Lines Must Meet at the Image Projection of the Screw Axis, m 54

Figure 3.9 Single Mirror Rectified Catadioptric Stereo Sensor 56
Figure 3.10 Region of Interaction 57
Figure 3.11 Illustration of Overlapping Fields of View 57
Figure 3.12 Behavior of Light at a Flat Reflective Surface 60
Figure 3.13 The Pinhole Camera 61
Figure 3.14 The View Angle of a Pinhole Camera 61
Figure 3.15 Measurements to be Taken to Find the Angle of View 64
Figure 3.16 Dimensions of Image 65
Figure 3.17 Mathematical Model 67
Figure 3.18 Illustration of Measurements 68
Figure 3.19 The Different Co-ordinate Bases 70
Figure 3.20 Location of Points in an Image 71
Figure 3.21 Similar Triangles 72
Figure 3.22 Trig/Geometric View of the Mathematical Model 75
Figure 3.23 Illustration of Reflecting the Point about the Mirror 77
Figure 3.24 Calculation of 5D/6D Information 78
Figure 3.25 The System of Axes after Applying All the Rotations 79
Figure 3.26 Spherical Polar Co-ordinates 80
Figure 3.27 System After Rotating by $-\phi$ and by $-(90 - \theta)$ 80
Figure 3.28 RGB Colour Space 84
Figure 3.29 HLS Color Model Viewed From Above 84
Figure 3.30 First Set of Constraints 86
Figure 3.31 Illustration of Image Moments 87
Figure 3.32 Features Calculated by Image Moments 87
Figure 3.33 SUSAN Masks at Different Positions in an Image 90
Figure 3.34 A Typical SUSAN Mask 92
Figure 3.35 Two Different Edge Types 93
Figure 3.36 Testing Contiguity 96
Figure 3.37 A simple Window Tracking System 97
Figure 3.38 Segmenting Occluded Objects 100

.

Figure 4.1 Flowchart of a General Reflections System 103
Figure 4.2 Flow Chart of the Computational Process 106
Figure 4.3 Components of a Virtual Drum Kit 108
Figure 4.4 A Yamaha Drum Kit 109
Figure 4.5 Visualization of the Original Virtual Drum Kit 111
Figure 4.6 Visualization of the Drum Kit in the CyberStage Implementation 114
Figure 4.7 Desktop Installation of the Camera and Mirrors for the Virtual Drums Application 115
Figure 4.8 Blue Drumsticks Tracked in the desktop Virtual Drums Installation 116
Figure 4.9 Light Stick Used in the CyberStage Virtual Drum Kit 117
Figure 4.10 The Computer Vision Algorithm Used in the Practical Implementation of the Virtual Drums Project 118
Figure 4.11 Illustration of a Catadioptric Stereo Image of a Blue Drumstick 119
Figure 4.12 SUSAN Applied to a Drumstick and a Piece of Paper 120
Figure 4.13 Image Moments of a Drumstick 121
Figure 4.14 Visualization of the Mathematical Model 122
Figure 4.15 Tracking a Blue Drumstick 123
Figure 4.16 Finding the Endpoints of a Drumstick 123
Figure 4.17 Illustration of the Test for One or Two Drumsticks 126
Figure 4.18 Ndebele Paintings 127
Figure 4.19 Ndebele Painting in VR 127
Figure 4.20 The Light Candle and Camera Used in Ndebele Painting 129
Figure 4.21 Reflections in Ndebele Paintings 129
Figure 5.1 Graph of Results of Trigonometric 3D Calculation 135
Figure 5.2 Accuracy of 3D Calculation using the Algebraic Approach 137
Figure 5.3 Image Moments of A4 Page Used in Angular Tests 139
Figure 5.4 Endpoints Found by Image Moments 139
Figure 5.5 Graph Illustrating the Number of Extreme Erroneous Results 141
Figure 5.6 Average Processing Time for the Reflections Algorithm 143
Figure 5.7 Processing Time for the Different Components of the System 144
Figure 5.8 Two different views of a Drumstick 146
Figure 5.9 Image Before Application of the Algorithms 148

Figure 5.10 Image After Chroma Keying is Applied to it 149
Figure 5.11 SUSAN Applied to Image 149
Figure 5.12 Affects of the Flood Fill Algorithm 150
Figure 5.13 Calculation of Image Moments 150
Figure 5.14 Region of Interaction in which Tracking is Performed 151
Figure 5.15 Number of Frames Object Tracked in Over 10 Seconds 151
Figure 5.16 Movement of the Drumstick Over 10 Seconds 152
Figure 5.17 Rapid Motion of Drumstick 153
Figure 5.18 Number of Frames for which the Drumstick is Tracked in the Different Views . 153
Figure 5.19 Effects of Rapid Movement on SUSAN Algorithm 154

List of Tables

Table 5.1 Trigonometric 3D Calculation Accuracy Results 135
Table 5.2 Algebraic 3D Calculation Accuracy Results 137
Table 5.3 Angular Accuracy Results 138
Table 5.4 Stability Results for 3D Calculation Using the Algebraic Approach 140
Table 5.5 Results of a Single Trial for Angular Stability 141
Table 5.6 Average Processing Time for the Reflections Algorithm 143
Table 5.7 Results of the Chroma Keying and SUSAN Algorithms 145
Table 5.8 Results of Image Moments and the Fast Flood Fill Algorithm 146
Table 5.9 Results of the 3D and 6D Calculation Algorithms 147
Table 5.10 Time to Track a Single Drumstick 147
Table 5.11 Total of the Combined Times for the Different Algorithms 148
Table 5.12 Tracking Results 152
Table 5.13 Tracking Results for Faster Movement 154