

Eduardo Bayro-Corrochano

Geometric Computing

For Wavelet Transforms,
Robot Vision, Learning,
Control and Action



Springer

Contents

Foreword	vii
Preface	ix
Part I Fundamentals of Geometric Algebra	
1 Introduction to Geometric Algebra	3
1.1 History of Geometric Algebra	3
1.2 What Is Geometric Algebra?	5
1.2.1 Basic Definitions	5
1.2.2 Nonorthonormal Frames and Reciprocal Frames	7
1.2.3 Some Useful Formulas	8
1.2.4 Multivector Products	8
1.2.5 Further Properties of the Geometric Product	11
1.2.6 Dual Blades and Duality in the Geometric Product	19
1.2.7 Multivector Operations	20
1.3 Linear Algebra	22
1.4 Simplexes	23
1.5 Geometric Calculus	25
1.5.1 Multivector-Valued Functions and the Inner Product	25
1.5.2 The Multivector Integral	26
1.5.3 The Vector Derivative	27
1.5.4 Grad, Div, and Curl	27
1.5.5 Multivector Fields	28
1.5.6 Convolution and Correlation of Scalar Fields	29
1.5.7 Clifford Convolution and Correlation	29
1.5.8 Linear Algebra Derivations	30
1.5.9 Reciprocal Frames with Curvilinear Coordinates	31
1.5.10 Geometric Calculus in 2D	31
1.5.11 Electromagnetism: The Maxwell Equations	32
1.5.12 Spinors, Schrödinger Pauli, and Dirac Equations	35
1.5.13 Spinor Operators	37
1.6 Exercises	39

2	Geometric Algebra for Modeling in Robot Physics	45
2.1	The Roots of Geometry and Algebra	45
2.2	Geometric Algebra: A Unified Mathematical Language	47
2.3	What Does Geometric Algebra Offer for Geometric Computing?	48
2.3.1	Coordinate-Free Mathematical System	48
2.3.2	Models for Euclidean and Pseudo- Euclidean Geometry	49
2.3.3	Subspaces as Computing Elements	50
2.3.4	Representation of Orthogonal Transformations	51
2.3.5	Objects and Operators	51
2.3.6	Extension of Linear Transformations	52
2.3.7	Signals and Wavelets in the Geometric Algebra Framework	53
2.3.8	Kinematics and Dynamics	53
2.4	Solving Problems in Perception and Action Systems	54

**Part II Euclidean, Pseudo-Euclidean, Lie and Incidence Algebras,
and Conformal Geometries**

3	2D, 3D, and 4D Geometric Algebras	63
3.1	Complex, Double, and Dual Numbers	63
3.2	2D Geometric Algebras of the Plane	64
3.3	3D Geometric Algebra for the Euclidean 3D Space	66
3.3.1	The Algebra of Rotors	67
3.3.2	Orthogonal Rotors	70
3.3.3	Recovering a Rotor	71
3.4	Quaternion Algebra	72
3.5	Lie Algebras and Bivector Algebras	74
3.5.1	Lie Group of Rotors	75
3.5.2	Bivector Lie Algebra	76
3.5.3	Complex Structures and Unitary Groups	77
3.5.4	Hermitian Inner Product and Unitary Groups	78
3.6	4D Geometric Algebra for 3D Kinematics	80
3.6.1	Motor Algebra	80
3.6.2	Motors, Rotors, and Translators in $\mathcal{G}_{3,0,1}^+$	82
3.6.3	Properties of Motors	85
3.7	4D Geometric Algebra for Projective 3D Space	87
3.8	Conclusion	88
3.9	Exercises	88
4	Kinematics of the 2D and 3D Spaces	93
4.1	Introduction	93
4.2	Representation of Points, Lines, and Planes Using 3D Geometric Algebra	93

4.3	Representation of Points, Lines, and Planes Using Motor Algebra	95
4.4	Representation of Points, Lines, and Planes Using 4D Geometric Algebra	96
4.5	Motion of Points, Lines, and Planes in 3D Geometric Algebra	97
4.6	Motion of Points, Lines, and Planes Using Motor Algebra	98
4.7	Motion of Points, Lines, and Planes Using 4D Geometric Algebra	100
4.8	Spatial Velocity of Points, Lines, and Planes	101
4.8.1	Rigid-Body Spatial Velocity Using Matrices	101
4.8.2	Angular Velocity Using Rotors	105
4.8.3	Rigid-Body Spatial Velocity Using Motor Algebra	108
4.8.4	Point, Line, and Plane Spatial Velocities Using Motor Algebra	109
4.9	Incidence Relations Between Points, Lines, and Planes	110
4.9.1	Flags of Points, Lines, and Planes	111
4.10	Conclusion	112
4.11	Exercises	112
5	Lie Algebras and the Algebra of Incidence Using the Null Cone and Affine Plane	117
5.1	Introduction	117
5.2	Geometric Algebra of Reciprocal Null Cones	118
5.2.1	Reciprocal Null Cones	118
5.2.2	The Universal Geometric Algebra $\mathcal{G}_{n,n}$	119
5.2.3	The Lie Algebra of Null Spaces	120
5.2.4	The Standard Bases of $\mathcal{G}_{n,n}$	122
5.2.5	Representations and Operations Using Bivector Matrices	123
5.2.6	Bivector Representation of Linear Operators	124
5.3	Horosphere and n -Dimensional Affine Plane	125
5.4	The General Linear Group	127
5.4.1	The General Linear Algebra $gl(\mathcal{N})$ of the General Linear Lie Group $GL(\mathcal{N})$	129
5.4.2	The Orthogonal Groups	130
5.5	Computing Rigid Motion in the Affine Plane	133
5.6	The Lie Algebra of the Affine Plane	134
5.7	The Algebra of Incidence	138
5.7.1	Incidence Relations in the Affine n -Plane	140
5.7.2	Directed Distances	141
5.7.3	Incidence Relations in the Affine 3-Plane	142
5.7.4	Geometric Constraints as Flags	144
5.8	Conclusion	144
5.9	Exercises	145

6	Conformal Geometric Algebra	149
6.1	Introduction	149
6.1.1	Conformal Split	150
6.1.2	Conformal Splits for Points and Simplexes	151
6.1.3	Euclidean and Conformal Spaces	152
6.1.4	Stereographic Projection	155
6.1.5	Inner- and Outer-Product Null Spaces	157
6.1.6	Spheres and Planes	158
6.1.7	Geometric Identities, Meet and Join Operations, Duals, and Flats	160
6.1.8	Meet, Pair of Points, and Plunge	166
6.1.9	Simplexes and Spheres	168
6.2	The 3D Affine Plane	169
6.2.1	Lines and Planes	170
6.2.2	Directed Distance	171
6.3	The Lie Algebra	172
6.4	Conformal Transformations	172
6.4.1	Inversion	173
6.4.2	Reflection	175
6.4.3	Translation	176
6.4.4	Transversion	176
6.4.5	Rotation	177
6.4.6	Rigid Motion Using Flags	177
6.4.7	Dilation	179
6.4.8	Involution	179
6.4.9	Conformal Transformation	180
6.5	Ruled Surfaces	180
6.5.1	Cone and Conics	180
6.5.2	Cycloidal Curves	181
6.5.3	Helicoid	182
6.5.4	Sphere and Cone	182
6.5.5	Hyperboloid, Ellipsoids, and Conoid	183
6.6	Exercises	183
7	Programming Issues	189
7.1	Main Issues for an Efficient Implementation	189
7.1.1	Specific Aspects for the Implementation	190
7.2	Implementation Practicalities	191
7.2.1	Specification of the Geometric Algebra, $\mathcal{G}_{p,q}$	191
7.2.2	The General Multivector Class	191
7.2.3	Optimization of Multivector Functions	192
7.2.4	Factorization	193
7.2.5	Speeding Up Geometric Algebra Expressions	194
7.2.6	Multivector Software Packets	195

Part III Geometric Computing for Image Processing, Computer Vision, and Neurocomputing

8	Clifford–Fourier and Wavelet Transforms	201
8.1	Introduction	201
8.2	Image Analysis in the Frequency Domain	201
8.2.1	The One-Dimensional Fourier Transform	202
8.2.2	The Two-Dimensional Fourier Transform	203
8.2.3	Quaternionic Fourier Transform	203
8.2.4	2D Analytic Signals	205
8.2.5	Properties of the QFT	208
8.2.6	Discrete QFT	211
8.3	Image Analysis Using the Phase Concept	213
8.3.1	2D Gabor Filters	213
8.3.2	The Phase Concept	214
8.4	Clifford–Fourier Transforms	214
8.4.1	Tri-Dimensional Clifford–Fourier Transform	217
8.4.2	Space and Time Geometric Algebra Fourier Transform	218
8.4.3	n -Dimensional Clifford–Fourier Transform	219
8.5	From Real to Clifford Wavelet Transforms for Multiresolution Analysis	219
8.5.1	Real Wavelet Transform	220
8.5.2	Discrete Wavelets	220
8.5.3	Wavelet Pyramid	223
8.5.4	Complex Wavelet Transform	223
8.5.5	Quaternion Wavelet Transform	225
8.5.6	Quaternionic Wavelet Pyramid	229
8.5.7	The Tridimensional Clifford Wavelet Transform	232
8.5.8	The Continuous Conformal Geometric Algebra Wavelet Transform	234
8.5.9	The n -Dimensional Clifford Wavelet Transform	235
8.6	Conclusion	236
9	Geometric Algebra of Computer Vision	237
9.1	Introduction	237
9.2	The Geometric Algebras of 3D and 4D Spaces	237
9.2.1	3D Space and the 2D Image Plane	238
9.2.2	The Geometric Algebra of 3D Euclidean Space	240
9.2.3	A 4D Geometric Algebra for Projective Space	240
9.2.4	Projective Transformations	241
9.2.5	The Projective Split	242
9.3	The Algebra of Incidence	244
9.3.1	The Bracket	245
9.3.2	The Duality Principle and Meet and Join Operations	246

9.4	Algebra in Projective Space	247
9.4.1	Intersection of a Line and a Plane	248
9.4.2	Intersection of Two Planes	249
9.4.3	Intersection of Two Lines	250
9.4.4	Implementation of the Algebra	250
9.5	Projective Invariants	251
9.5.1	The 1D Cross-Ratio	251
9.5.2	2D Generalization of the Cross-Ratio	253
9.5.3	3D Generalization of the Cross-Ratio	254
9.6	Visual Geometry of n -Uncalibrated Cameras	255
9.6.1	Geometry of One View	255
9.6.2	Geometry of Two Views	259
9.6.3	Geometry of Three Views	261
9.6.4	Geometry of n -Views	263
9.7	Omnidirectional Vision	264
9.7.1	Omnidirectional Vision and Geometric Algebra	265
9.7.2	Point Projection	266
9.7.3	Inverse Point Projection	267
9.8	Invariants in the Conformal Space	268
9.8.1	Invariants and Omnidirectional Vision	269
9.8.2	Projective and Permutation p^2 -Invariants	271
9.9	Conclusion	273
9.10	Exercises	273

10	Geometric Neuralcomputing	277
10.1	Introduction	277
10.2	Real-Valued Neural Networks	278
10.3	Complex MLP and Quaternionic MLP	279
10.4	Geometric Algebra Neural Networks	280
10.4.1	The Activation Function	280
10.4.2	The Geometric Neuron	281
10.4.3	Feedforward Geometric Neural Networks	283
10.4.4	Generalized Geometric Neural Networks	284
10.4.5	The Learning Rule	285
10.4.6	Multidimensional Back-Propagation Training Rule	285
10.4.7	Simplification of the Learning Rule Using the Density Theorem	286
10.4.8	Learning Using the Appropriate Geometric Algebras ..	287
10.5	Support Vector Machines in Geometric Algebra	288
10.6	Linear Clifford Support Vector Machines for Classification	288
10.7	Nonlinear Clifford Support Vector Machines For Classification ..	292
10.8	Clifford SVM for Regression	294
10.9	Conclusion	296

Part IV Geometric Computing of Robot Kinematics and Dynamics

11 Kinematics	299
11.1 Introduction	299
11.2 Elementary Transformations of Robot Manipulators	299
11.2.1 The Denavit–Hartenberg Parameterization	300
11.2.2 Representations of Prismatic and Revolute Transformations	301
11.2.3 Grasping by Using Constraint Equations	304
11.3 Direct Kinematics of Robot Manipulators	306
11.3.1 MAPLE Program for Motor Algebra Computations	307
11.4 Inverse Kinematics of Robot Manipulators Using Motor Algebra	308
11.4.1 The Rendezvous Method	309
11.4.2 Computing θ_1 , θ_2 , and d_3 Using a Point	309
11.4.3 Computing θ_4 and θ_5 Using a Line	312
11.4.4 Computing θ_6 Using a Plane Representation	314
11.5 Inverse Kinematics Using the 3D Affine Plane	315
11.6 Inverse Kinematic Using Conformal Geometric Algebra	318
11.7 Conclusion	322
12 Dynamics	325
12.1 Introduction	325
12.2 Differential Kinematics	325
12.3 Dynamics	328
12.3.1 Kinetic Energy	328
12.3.2 Potential Energy	335
12.3.3 Lagrange’s Equations	335
12.4 Complexity Analysis	343
12.4.1 Computing \mathcal{M}	343
12.4.2 Computing G	343
12.5 Conclusion	344

Part V Applications I: Image Processing, Computer Vision, and Neurocomputing

13 Applications of Lie Filters, and Quaternion Fourier and Wavelet Transforms	347
13.1 Lie Filters in the Affine Plane	347
13.1.1 The Design of an Image Filter	348
13.1.2 Recognition of Hand Gestures	349
13.2 Representation of Speech as 2D Signals	350
13.3 Preprocessing of Speech 2D Representations Using the QFT and Quaternionic Gabor Filter	352
13.3.1 Method 1	352
13.3.2 Method 2	354

13.4	Recognition of French Phonemes Using Neurocomputing	355
13.5	Application of QWT	357
13.5.1	Estimation of the Quaternionic Phase	358
13.5.2	Confidence Interval	359
13.5.3	Discussion on Similarity Distance and the Phase Concept	360
13.5.4	Optical Flow Estimation	361
13.6	Conclusion	365

14 Invariants Theory in Computer Vision

	and Omnidirectional Vision	367
14.1	Introduction	367
14.2	Conics and Pascal's Theorem	368
14.3	Computing Intrinsic Camera Parameters	371
14.4	Projective Invariants	372
14.4.1	The 1D Cross-Ratio	373
14.4.2	2D Generalization of the Cross-Ratio	374
14.4.3	3D Generalization of the Cross-Ratio	376
14.4.4	Generation of 3D Projective Invariants	377
14.5	3D Projective Invariants from Multiple Views	381
14.5.1	Projective Invariants Using Two Views	381
14.5.2	Projective Invariant of Points Using Three Uncalibrated Cameras	383
14.5.3	Comparison of the Projective Invariants	385
14.6	Visually Guided Grasping	387
14.6.1	Parallel Orienting	387
14.6.2	Centering	389
14.6.3	Grasping	389
14.6.4	Holding the Object	390
14.7	Camera Self-Localization	390
14.8	Projective Depth	391
14.9	Shape and Motion	393
14.9.1	The Join-Image	394
14.9.2	The SVD Method	395
14.9.3	Completion of the 3D Shape Using Invariants	396
14.10	Omnidirectional Vision Landmark Identification	
	Using Projective Invariants	398
14.10.1	Learning Phase	398
14.10.2	Recognition Phase	399
14.10.3	Omnidirectional Vision and Invariants for Robot Navigation	400
14.10.4	Learning Phase	401
14.10.5	Recognition Phase	401
14.10.6	Quantitative Results	402
14.11	Conclusions	403

15	Registration of 3D Points Using GA and Tensor Voting	405
15.1	Problem Formulation	405
15.1.1	The Geometric Constraint	406
15.2	Tensor Voting	409
15.2.1	Tensor Representation in 3D	409
15.2.2	Voting Fields in 3D	410
15.2.3	Detection of 3D Surfaces	414
15.2.4	Estimation of 3D Correspondences	415
15.3	Experimental Analysis	417
15.3.1	Correspondences Between 3D Points by Rigid Motion	417
15.3.2	Multiple Overlapping Motions and Nonrigid Motion	419
15.3.3	Extension to Nonrigid Motion	420
15.4	Conclusions	422
16	Applications in Neuralcomputing	425
16.1	Experiments Using Geometric Feedforward Neural Networks	425
16.1.1	Learning a High Nonlinear Mapping	425
16.1.2	Encoder–Decoder Problem	426
16.1.3	Prediction	428
16.2	Experiments Using Clifford Support Vector Machines	429
16.2.1	3D Spiral: Nonlinear Classification Problem	430
16.2.2	Object Recognition	432
16.2.3	Multi-Case Interpolation	440
16.3	Conclusion	442
17	Neural Computing for 2D Contour and 3D Surface Reconstruction	443
17.1	Determining the Shape of an Object	443
17.1.1	Automatic Sample Selection Using GGVF	444
17.1.2	Learning the Shape Using Versors	446
17.2	Experiments	448
17.3	Conclusion	455

Part VI Applications II: Robotics and Medical Robotics

18	Rigid Motion Estimation Using Line Observations	459
18.1	Introduction	459
18.2	Batch Estimation Using SVD Techniques	459
18.2.1	Solving $AX = XB$ Using Motor Algebra	461
18.2.2	Estimation of the Hand–Eye Motor Using SVD	464
18.3	Experimental Results	466
18.4	Discussion	470
18.5	Recursive Estimation Using Kalman Filter Techniques	470
18.5.1	The Kalman Filter	470
18.5.2	The Extended Kalman Filter	472
18.5.3	The Rotor-Extended Kalman Filter	474

18.6	The Motor-Extended Kalman Filter.....	477
18.6.1	Representation of the Line Motion Model in Linear Algebra	478
18.6.2	Linearization of the Measurement Model	480
18.6.3	Enforcing a Geometric Constraint	481
18.6.4	Operation of the MEKF Algorithm	483
18.6.5	Estimation of the Relative Positioning of a Robot End-Effector	486
18.7	Conclusion	490
19	Tracker Endoscope Calibration and Body-Sensors' Calibration	491
19.1	Camera Device Calibration	491
19.1.1	Rigid Body Motion in CGA	491
19.1.2	Hand-Eye Calibration in CGA	493
19.1.3	Tracker Endoscope Calibration	494
19.2	Body-Sensor Calibration	497
19.2.1	Body-Eye Calibration	498
19.2.2	Algorithm Simplification	501
19.3	Conclusions	503
20	Tracking, Grasping, and Object Manipulation	505
20.1	Tracking	505
20.1.1	Exact Linearization via Feedback	506
20.1.2	Visual Jacobian	508
20.1.3	Exact Linearization via Feedback	509
20.1.4	Experimental Results	510
20.2	Barrett Hand Direct Kinematics	512
20.3	Pose Estimation	514
20.3.1	Segmentation	515
20.3.2	Object Projection	516
20.4	Grasping Objects	518
20.4.1	First Style of Grasping	519
20.4.2	Second Style of Grasping	521
20.4.3	Third Style of Grasping	521
20.5	Target Pose	522
20.5.1	Object Pose	524
20.6	Visually Guided Grasping	524
20.6.1	Results	525
20.7	Fuzzy Logic and Conformal Geometric Algebra for Grasping	525
20.7.1	Mamdani Fuzzy System	526
20.7.2	Direct Kinematics of the Barrett Hand	527
20.7.3	Fuzzy Grasping of Objects	528
20.8	Conclusion	531

21	3D Maps, Navigation, and Relocalization	533
21.1	Map Building	533
21.1.1	Matching Laser Readings	533
21.1.2	Map Building	536
21.1.3	Line Map	536
21.1.4	3D Map Building	538
21.2	Navigation	540
21.2.1	Localization	540
21.2.2	Adding Objects to the 3D Map	540
21.2.3	Path Following	541
21.3	3D Map Building Using Laser and Stereo Vision	545
21.3.1	Laser Rangefinder	548
21.3.2	Stereo Camera System with Pan-Tilt Unit	550
21.4	Relocation Using Lines and the Hough Transform	551
21.5	Experiments	554
21.6	Conclusions	555
22	Modeling and Registration of Medical Data	557
22.1	Background	557
22.1.1	Union of Spheres	557
22.1.2	The Marching Cubes Algorithm	558
22.2	Segmentation	559
22.3	Marching Spheres	563
22.3.1	Experimental Results for Modeling	564
22.4	Registration of Two Models	567
22.4.1	Sphere Matching	567
22.4.2	Experimental Results for Registration	570
22.5	Conclusions	572
Part VII Appendix		
23	Clifford Algebras and Related Algebras	575
23.1	Clifford Algebras	575
23.1.1	Basic Properties	575
23.1.2	Definitions and Existence	576
23.1.3	Real and Complex Clifford Algebras	577
23.1.4	Involutions	579
23.1.5	Structure and Classification of Clifford Algebras	579
23.1.6	Clifford Groups, Pin and Spin Groups, and Spinors	581
23.2	Related Algebras	584
23.2.1	Gibbs' Vector Algebra	584
23.2.2	Exterior Algebras	586
23.2.3	Grassmann–Cayley Algebras	590
24	Notation	595

25 Useful Formulas for Geometric Algebra	597
References	603
Index	613