Pure Mathematics Topics in the Unified Robotics Curriculum

> *Extracted from unified-robotics-curriculum.md. This lists every distinct mathematics topic that appears across the curriculum — both as standalone prerequisite coursework and as mathematical tools embedded within robotics courses.*

1. Calculus

Topic	Where It Appears
Limits & continuity	Foundation 1.1 — Calculus I
Single-variable differentiation	Foundation 1.1 — Calculus I
Single-variable integration	Foundation 1.1 — Calculus I
Infinite series & convergence	Foundation 1.1 — Calculus II
Multivariable calculus (partial derivatives, gradients)	Foundation 1.1 — Calculus II; Pillar 4 (control); Optimization
Vector calculus (div, curl, flux, line/surface integrals)	Foundation 1.1 — Calculus II; Foundation 1.2 — Electromagnetism
Calculus of variations	Pillar 1 — Lagrangian mechanics; Pillar 4 — Optimal control

2. Linear Algebra

Topic	Where It Appears
Vectors, vector spaces, subspaces	Foundation 1.1; all pillars
Matrix operations & matrix algebra	Foundation 1.1; Pillar 1 — Kinematics
Systems of linear equations	Foundation 1.1; Pillar 4 — State-space control
Eigenvalues & eigenvectors	Foundation 1.1; Pillar 4 — Stability analysis
Singular Value Decomposition (SVD)	Foundation 1.1; Pillar 2 — Computer vision
Least squares & pseudo-inverses	Foundation 1.1; Pillar 1 — Inverse kinematics; Pillar 4 — Estimation
Rotation matrices	Pillar 1 — Robot kinematics
Homogeneous transformations (SE(3))	Pillar 1 — Forward/inverse kinematics
Jacobian matrices	Pillar 1 — Velocity kinematics; Pillar 4 — Linearization
Positive definite / semidefinite matrices	Pillar 4 — LQR, Lyapunov; Optimization
Matrix exponentials	Pillar 1 — Rigid body motion; Pillar 4 — State-space
Rank, nullspace, range	Pillar 1 — Singularity analysis; Foundation 1.1

Topic	Where It Appears
Inner products & norms	Foundation 1.1; Pillar 3 — Planning cost functions
Linear transformations	Foundation 1.1; Pillar 1 — Coordinate transforms

3. Differential Equations

Topic	Where It Appears
First-order ODEs	Foundation 1.1; Pillar 4 — Control systems
Higher-order linear ODEs	Foundation 1.1; Pillar 1 — Dynamics
Systems of ODEs	Foundation 1.1; Pillar 4 — State-space control
Laplace transforms	Foundation 1.1; Pillar 4 — Transfer functions
Stability of equilibria	Pillar 4 — Lyapunov stability, nonlinear control
Phase portraits & qualitative analysis	Pillar 4 — Nonlinear control
Numerical ODE solvers (Euler, Runge-Kutta)	Foundation 1.1 — Numerical methods; Spec 3.8 — Simulation
Neural ODEs	Spec 3.8 — Physics-based deep learning

4. Probability & Statistics

Topic	Where It Appears
Probability axioms & combinatorics	Foundation 1.1
Random variables (discrete & continuous)	Foundation 1.1; Pillar 2 — Perception
Probability distributions (Gaussian, uniform, Poisson, etc.)	Foundation 1.1; Pillar 2 — Sensor models
Joint, marginal, and conditional probability	Foundation 1.1; Pillar 3 — Probabilistic robotics
Bayes' theorem & Bayesian inference	Foundation 1.1; Pillar 2 — SLAM; Pillar 3 — Probabilistic robotics
Expectation, variance, covariance	Foundation 1.1; Pillar 4 — Kalman filtering
Covariance matrices	Pillar 2 — Sensor fusion; Pillar 4 — EKF
Maximum likelihood estimation (MLE)	Pillar 2 — Perception; Spec 3.3 — Deep learning
Maximum a posteriori estimation (MAP)	Pillar 2 — SLAM
Gaussian processes	Spec 3.3 — Robot learning

Topic	Where It Appears
Markov chains & stochastic processes	Pillar 3 — MDPs, POMDPs
Hidden Markov Models (HMMs)	Pillar 3 — Probabilistic robotics
Statistical hypothesis testing	Foundation 1.1
Monte Carlo methods	Pillar 2 — Particle filters; Pillar 3 — Sampling-based planning

5. Optimization

Topic	Where It Appears
Unconstrained optimization (gradient descent, Newton's method)	Foundation 1.1; Spec 3.3 — Deep learning
Constrained optimization (Lagrange multipliers, KKT conditions)	Foundation 1.1; Pillar 3 — Trajectory optimization
Convex optimization	Foundation 1.1 — Optimization; Pillar 4 — LQR; Stanford EE 364A
Linear programming	Foundation 1.1 — Optimization
Quadratic programming	Pillar 4 — MPC; Pillar 3 — Trajectory optimization
Nonlinear programming	Foundation 1.1; Pillar 3 — Motion planning
Dynamic programming	Pillar 3 — MDPs; Pillar 4 — Optimal control
Gradient methods (SGD, Adam)	Spec 3.3 — Deep learning, reinforcement learning
Semidefinite programming	Pillar 4 — Robust control (advanced)

6. Geometry & Topology

Topic	Where It Appears
Euclidean geometry (distances, angles, planes)	Pillar 1 — Kinematics; Pillar 2 — Vision
Rotation representations: Euler angles	Pillar 1 — Robot kinematics
Rotation representations: quaternions	Pillar 1 — Robot kinematics
Rotation representations: axis-angle	Pillar 1 — Robot kinematics
Lie groups SO(3), SE(3)	Pillar 1 — Rigid body motion
Lie algebra so(3), se(3)	Pillar 1 — Velocity kinematics
Configuration space (C-space)	Pillar 3 — Motion planning
Workspace analysis	Pillar 1 — Mechanism design

Topic	Where It Appears
Degrees of freedom & constraint analysis	Pillar 1 — Mechanism design
Projective geometry	Pillar 2 — Camera models, epipolar geometry
Manifolds (basic concepts)	Pillar 1 — Configuration spaces; Pillar 3 — Planning
Convex sets & convex hulls	Pillar 3 — Collision detection; Optimization
Voronoi diagrams & Delaunay triangulation	Pillar 3 — Motion planning

7. Graph Theory & Discrete Mathematics

Topic	Where It Appears
Graphs (vertices, edges, directed/undirected)	Pillar 3 — Planning; Foundation 1.3 — Algorithms
Graph search: BFS, DFS	Foundation 1.3 — Data structures & algorithms
Shortest path: Dijkstra’s, A*, D*	Pillar 3 — Motion planning
Trees and tree search	Pillar 3 — RRT, behavior trees
Graph-based SLAM (pose graphs)	Pillar 2 — SLAM; Spec 3.2
Combinatorics	Foundation 1.1 — Probability; Pillar 3 — Task planning
Logic (propositional, first-order)	Pillar 3 — AI
Complexity analysis (Big-O)	Foundation 1.3 — Algorithms

8. Fourier Analysis & Signal Processing

Topic	Where It Appears
Fourier series	Foundation 1.2 — Signals & systems
Fourier transform (continuous & discrete / FFT)	Foundation 1.2; Pillar 2 — Image processing
Frequency domain analysis (Bode plots, Nyquist)	Pillar 4 — Feedback control
Z-transform	Foundation 1.2 — Discrete-time systems
Laplace transform	Foundation 1.1 — Diff. Eq.; Pillar 4 — Transfer functions
Convolution	Foundation 1.2; Pillar 2 — Computer vision (CNNs)
Sampling theorem (Nyquist–Shannon)	Foundation 1.2 — Signals & systems
Filtering (low-pass, band-pass, Kalman)	Foundation 1.2; Pillar 2 — Sensor filtering; Pillar 4 — Estimation

9. Numerical Methods

Topic	Where It Appears
Numerical linear algebra (LU, QR, Cholesky decomposition)	Foundation 1.1 — Numerical methods
Numerical integration (quadrature)	Foundation 1.1; Spec 3.8 — Simulation
Numerical ODE solvers (Euler, RK4, adaptive step)	Foundation 1.1; Spec 3.8 — Robot dynamics & simulation
Root finding (Newton-Raphson, bisection)	Foundation 1.1; Pillar 1 — Inverse kinematics
Interpolation & splines	Foundation 1.1; Pillar 1 — Trajectory planning
Finite element methods (FEA)	Spec 3.8 — Computational design
Numerical stability & conditioning	Foundation 1.1 — Numerical methods

Summary by Curriculum Area

Math Domain	Prerequisite (Part 1)	Core Pillars (Part 2)	Specializations (Part 3)
Calculus	●	●	●
Linear Algebra	●	●	●
Differential Equations	●	●	●
Probability & Statistics	●	●	●
Optimization	●	●	●
Geometry & Topology		●	●
Graph Theory & Discrete Math	●	●	
Fourier Analysis & Signals	●	●	
Numerical Methods	●		●

Derived from the unified robotics curriculum consolidating MIT, CMU, Stanford, UMich, Georgia Tech, UC Berkeley, UPenn, UW, JHU, and UT Austin.