Precision Engineering for Robotics

Course Outline | 120 Hours | 8 Chapters

TARGET AUDIENCE

This programme is designed for mechanical, mechatronics and robotics engineers, product designers, and technical professionals who design, build or maintain robotic systems and want to create mechanisms that are accurate, repeatable and reliable. It suits early-career engineers moving into robotics product design, experienced CAD users who want to understand the engineering principles behind precise mechanisms, and cross-functional team members (such as test, manufacturing or quality engineers) who need a working knowledge of how precision is designed into robot assemblies. Participants should be comfortable with basic engineering mechanics and 3D CAD modelling; no prior background in precision engineering is required.

PREREQUISITE CHECKLIST

- ☐ Engineering statics: free body diagrams, forces, moments and equilibrium
- ☐ Strength of materials: stress, strain, bending, torsion and beam deflection
- ☐ Mathematics: trigonometry, vectors, basic matrices and unit conversions
- ☐ Basic statistics: mean, standard deviation and normal distribution
- ☐ Reading engineering drawings: views, dimensions and basic tolerances
- ☐ Awareness of common manufacturing processes (machining, sheet metal, 3D printing)
- ☐ General familiarity with motors, gears and bearings
- ☐ Working knowledge of 3D CAD modelling, assemblies and drawings

COURSE OUTCOMES

- **Understand** the core principles of precision engineering, including accuracy, repeatability, resolution, exact constraint and the Abbe principle, and how they apply to robotic systems.
- **Apply** exact-constraint and kinematic design principles to create mounts, fixtures and interfaces that locate precisely and repeatably.
- **Create** detailed Fusion 360 models, drawings and simulations of precision robot components, including kinematic couplings, flexures and joint assemblies.
- **Optimize** robot joint and structure designs for stiffness, thermal stability, low backlash and manufacturability.
- **Troubleshoot** accuracy and repeatability problems in robotic assemblies by tracing them to root causes such as over-constraint, misalignment, runout, deflection or thermal drift.
- **Analyze** tolerance stack-ups, structural loops and error sources using both worst-case and statistical methods.
- **Design** precision robot subsystems by selecting appropriate motors, encoders, bearings, transmissions and couplings.
- **Implement** measurement, repeatability testing and calibration procedures, including reversal and self-calibration techniques.

- **Evaluate** complete designs using error budgets, GD&T and design reviews to verify they meet precision requirements.

COURSE OBJECTIVES

- Build a strong conceptual foundation in precision engineering principles and their relevance to robotics product design.
- Develop practical skills in designing, specifying and verifying precise robot mechanisms using Fusion 360.
- Equip participants to identify, quantify and control the error sources that limit the accuracy of robotic systems.
- Enable participants to plan measurement and calibration strategies that correct systematic errors in real hardware.
- Prepare participants to deliver a complete, well-justified precision subsystem design suitable for design review and manufacture.

COURSE OUTLINE

The course comprises 120 hours of theory and labs and is divided into 8 different chapters. Each chapter will be followed by hands-on lab exercises to reinforce learning and gauge understanding of the topics covered.

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CHAPTER 4: Tolerancing, GD&T and Stack-Up Analysis — 16 Hours

- Tolerance vs cost and limits and fits (ISO 286)
- Drawing standards and introduction to datums
- Datum reference frames and 3-2-1 locating
- Form tolerances: flatness, straightness, circularity and cylindricity
- Orientation tolerances: perpendicularity, parallelism and angularity
- Position tolerance, MMC, LMC and bonus tolerance
- Runout and profile tolerances
- Inspecting GD&T: how features are measured
- Worst-case tolerance stack-ups
- Statistical stack-ups: RSS and Monte Carlo concept
- Tolerance allocation and design for manufacture
- **Lab:** Apply GD&T to a joint housing and perform a motor–coupler–encoder stack-up

CHAPTER 5: Precision Drives, Bearings and Transmissions — 16 Hours

- Robot joint requirements: torque, speed, stiffness and precision
- Motor types: DC, BLDC and stepper; torque–speed characteristics
- Motor sizing: inertia matching, RMS torque and duty cycle
- Encoders: absolute vs incremental, resolution vs accuracy and mounting errors
- Bearings: types, preload, stiffness, runout and crossed-roller bearings
- Bearing arrangement and selection for robot joints
- Gear transmissions: planetary, harmonic and cycloidal drives
- Linear motion: ball screws, lead screws, guides and belts
- Shaft couplings and misalignment
- Backlash and lost motion: sources and mitigation
- **Lab:** Size and model a precision robot joint in Fusion 360

CHAPTER 6: Stiffness, Structural and Thermal Design — 12 Hours

- Deflection as error and the structural loop
- Stiffness of components and bolted interfaces; springs in series and parallel
- Material selection for stiffness and stability using Ashby charts
- FEA for stiffness in Fusion 360: setup, boundary conditions and sanity checks
- Natural frequency and vibration basics
- Thermal expansion, gradients and heat sources in robots
- Thermal design strategies: symmetry, material matching and thermal centres
- **Lab:** FEA of an arm link and thermal drift estimate of a sensor mount

CHAPTER 7: Error Budgeting and Calibration 16 Hours

- Error budgets: purpose and structure
- Identifying error sources and sensitivity analysis
- Combining errors: worst case vs RSS, systematic vs random
- Error modelling with homogeneous transforms
- Error budget for a robot joint and arm
- Using error budgets to make design decisions
- Calibration principles: what can and cannot be corrected
- Reversal, redundancy and self-calibration techniques
- Camera calibration methods and their limits
- Case study: binocular camera rig parallel-position calibration
- **Lab:** Build a spreadsheet error budget and draft a calibration procedure

CHAPTER 8: Capstone Project: Precision Robot Subsystem Design 20 Hours

- Project brief and requirements definition
- Concept generation and concept selection
- Constraint analysis and locating strategy
- Drive, bearing and transmission selection
- Detailed Fusion 360 modelling and GD&T drawings
- FEA stiffness and thermal verification
- Error budget, calibration and test plan
- DFM and serviceability review
- Final presentation and peer design review