# Introduction to Modern Robotics

# Configuration Space

Foundations of Robot Motion

Degrees of Freedom of a Rigid Body

Degrees of Freedom of a Robot

Configuration Space Topology

Configuration Space Representation

Configuration and Velocity Constraints

Task Space and Workspace

# Rigid-Body Motions

Introduction to Rigid-Body Motion

Rotation Matrices

Angular Velocities

Exponential Coordinates of Rotation

Homogeneous Transformation Matrices

Twists

Exponential Coordinates of Rigid-Body Motion

Wrenches

# Forward Kinematics

Product of Exponentials Formula in the Space Frame

Product of Exponentials Formula in the End-Effector Frame

Forward Kinematics Example

# Velocity Kinematics and Statics

Velocity Kinematics and Statics

Space Jacobian

Body Jacobian

Statics of Open Chains

Singularities

Manipulability

# Inverse Kinematics

Inverse Kinematics of Open Chains

Numerical Inverse Kinematics

# Kinematics of Closed Chains

Kinematics of Closed Chains

Lecture Comprehension Kinematics of Closed Chains

# Dynamics of Open Chains

Lagrangian Formulation of Dynamics

Understanding the Mass Matrix

Dynamics of a Single Rigid Body

Newton-Euler Inverse Dynamics

Forward Dynamics Open Chains

Dynamics in the Task Space

Constrained Dynamics

Actuation, Gearing, and Friction

# Trajectory Generation

Point-to-Point Trajectories

Polynomial Via Point Trajectories

Time-Optimal Time Scaling

# Motion Planning

Overview of Motion Planning

C-Space Obstacles

Graphs and Trees

Graph Search

Complete Path Planners

Grid Methods for Motion Planning

Sampling Methods for Motion Planning

Virtual Potential Fields

Nonlinear Optimization

# Robot Control

Control System Overview

Error Response

Linear Error Dynamics

First-Order Error Dynamics

Second-Order Error Dynamics

Motion Control with Velocity Inputs

Motion Control with Torque or Force Inputs

Force Control

Hybrid Motion-Force Control

# Grasping and Manipulation

Grasping and Manipulation

First-Order Analysis of a Single Contact

Contact Types: Rolling, Sliding and Breaking

Multiple Contacts

Planar Graphical Methods

Form Closure

Friction

Force Closure

Duality of Force and Motion Freedoms

Manipulation and the Meter-Stick Trick

Transport of an Assembly

# Wheeled Mobile Robots

Wheeled Mobile Robots

Omnidirectional Wheeled Mobile Robots

Modeling of Nonholonomic Wheeled Mobile Robots

Controllability of Wheeled Mobile Robots

Motion Planning for Nonholonomic Mobile Robots

Feedback Control for Nonholonomic Mobile Robots

Odometry

Mobile Manipulation

**Introduction to Aerial Robotics**

Unmanned Aerial Vehicles

Quadrotors

Key Components of Autonomous Flight

State Estimation

Applications

Meet the TAs

Basic Mechanics

Dynamic and 1-D Linear Control

Design Considerations

Agility and Maneuverability

Component Selection

Effects of Size

Supplementary Material

# Geometry and Mechanics

Transformations

Rotations

Euler Angles

Axis/Angle Representation for Rotations

Angular Velocity

Supplementary Material

Formulation

Newton-Euler Equations

Principal Axes and Principal Moments of Inertia

Quadrotor Equations of Motion

Supplementary Material

# Planning and Control

2-D Quadrotor Control

3-D Quadrotor Control

Time, Motion, and Trajectories

Motion Planning for Quadrotors

Supplementary Material

# Advanced Topics

Sensing and Estimation

Nonlinear Control

Control of Multiple Robots

Adjourn

Supplementary Material

# Introduction and Graph-based Plan Methods

Introduction to Computational Motion Planning

Grassfire Algorithm

Dijkstra’s Algorithm

A\* Algorithm

# Configuration Space

Introduction to Configuration Space

RR arm

Piano Mover’s Problem

Visibility Graph

Trapezoidal Decomposition

Collision Detection and Freespace Sampling Methods

# Sampling-based Planning Methods

Introduction to Probabilistic Road Maps

Issues with Probabilistic Road Maps

Introduction to Rapidly Exploring Random Trees

# Artificial Potential Field Methods

Constructing Artificial Potential Fields

Issues with Local Minima

Generalizing Potential Fields

# Mobility

Why and how do animals move?

Bioinspiration

Legged Mobility: Dynamic Motion and the Management of Energy

Review LTI Mechanical Dynamic Systems

Introduce Nonlinear Mechanical Dynamical Systems

Linearization & Normal Forms

# Behavioral & Physical

Walking like a rimless wheel

Running Like a Spring**-**loaded Pendulum

Metrics and Scaling

Design: Figures of Merit, Robustness

Actuator Technologies

# Anchors: Embodied Behaviors

Review of Kinematics

Review Dynamics and Control

Sprawled Posture Runners

Quadrupeds

Bipeds

# Composition

Sequential and Parallel Composition

Compositions of Vertical Hoppers

Same Composition, Different Bodies

Same Body, Different Composition

Transitions: RHex, Jerboa, and Minitaur Leaping

# Geometry of Image Formation

Introduction

Camera Modeling

Single View Geometry

More on Perspective Projection

Glimpse on Vanishing Points

Perspective Projection

Point-Line Duality

Rotations and Translations

Pinhole Camera Model

Focal Length and Dolly Zoom Effect

Intrinsic Camera Parameter

3D World to First Person Transformation

How to Compute Intrinsic from Vanishing Points

Camera Calibration

# Projective Transformations

Vanishing Points; How to Compute Camera Orientation

Compute Projective Transformation

Projective Transformations and Vanishing Points

Cross Ratios and Single View Metrology

Two View Soccer Metrology

# Pose Estimation

Visual Features

Singular Value Decomposition

RANSAC: Random Sample Consensus I

Pose from 3D Point Correspondences: The Procrustes Problem

Pose from Projective Transformations

Pose from Point Correspondence P3P

# Multi-View Geometry

Epipolar Geometry

RANSAC: Random Sample Consensus II

Nonlinear Least Squares

Optical Flow: 2D Point Correspondences

3D Velocities form Optical Flow

3D Motion and Structure from Multiple Views

Visual Odometry

Bundle Adjustment

# Gaussian Model Learning

1D Gaussian Distribution

Maximum Likelihood Estimate (MLE)

Multivariate Gaussian Distribution

MLE of Multivariate Gaussian

Gaussian Mixture Model (GMM)

GMM Parameter Estimation via EM

Expectation-Maximization (EM)

# Bayesian Estimation – Target Tracking

Kalman Filter Motivation

System and Measurement Models

Maximum-A-Posterior Estimation

Extended Kalman Filter and Unscented Kalman Filter

# Mapping

Introduction to Mapping

Occupancy Grid Map

Log-odd Update

Handling Range Sensor

Introduction to 3D Mapping

# Bayesian Estimation – Localization

Odometry Modeling

Map Registration

Particle Filter

Iterative Closest Point