02 Mechatronics Concepts

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Contents

1 Mechatronics Concepts - Vision-Based Pick and Place System

1.1 Overview

Mechatronics integrates **Mechanical Engineering**, **Electrical Engineering**, **Electronics**, and **Computer Science** to create intelligent systems. This document outlines all mechatronics concepts applied in the vision-based pick-and-place robotic system.

1.2 1. Mechanical Systems

1.2.1 1.1 Robot Manipulator Mechanics

1.2.1.1 1.1.1 Kinematic Chain

- **Concept:** Serial/parallel linkage configuration
- **Types:**
  - Serial manipulator (6-DOF arm: UR5, ABB, KUKA)
  - SCARA (Selective Compliance Assembly Robot Arm)
  - Delta robot (parallel kinematics)
- **Application:**
  - Workspace coverage analysis
  - Reachability studies
  - Joint limit constraints

1.2.1.2 1.1.2 Degrees of Freedom (DOF)

- **Minimum DOF:** 3 for positioning + 3 for orientation = 6 DOF
- **Redundancy:** >6 DOF for obstacle avoidance and singularity handling
- **Application:** Task-specific DOF selection

1.2.1.3 1.1.3 Link Geometry & D-H Parameters

- **Denavit-Hartenberg Convention:**
  - Link length (a)
  - Link twist ( )

  - Link offset (d)
  - Joint angle ( )
- **Application:**
  - Forward kinematics modeling
  - URDF generation

1.2.2 1.2 End-Effector (Gripper) Mechanisms

1.2.2.1 1.2.1 Gripper Types

- **Parallel Jaw Gripper:**
  - Two-finger, symmetric closure
  - Force transmission through linear actuation
- **Suction Gripper:**
  - Vacuum-based (for flat, non-porous objects)
  - Venturi effect or vacuum pump
- **Adaptive Gripper:**
  - Soft robotics, compliant fingers
  - Underactuated mechanisms

1.2.2.2 1.2.2 Gripper Kinematics & Force Analysis

- **Grasp Force Calculation:**

```
F_grasp =   * N (friction force)
Object weight: W = m * g
Minimum normal force: N = W / (2 *  )
```

- **Gripper Opening Range:** Adjustable for object size variation
- **Compliance:** Spring-loaded fingers for delicate objects

1.2.3 1.3 Structural Dynamics

1.2.3.1 1.3.1 Rigid Body Dynamics

- **Equations of Motion:**
  - Lagrangian mechanics
  - Newton-Euler recursive formulation
- **Inertia Matrix:** M(q)
- **Coriolis/Centrifugal Forces:** C(q, $\dot{q}$)
- **Gravity Vector:** G(q)
- **Equation:** M(q)$\ddot{q}$ + C(q,$\dot{q}$)$\dot{q}$ + G(q) =

1.2.3.2 1.3.2 Vibration Analysis

- **Natural Frequencies:** Avoid resonance
- **Damping:** Minimize oscillations during motion
- **Application:** Trajectory planning to reduce vibrations

1.2.4 1.4 Transmission Mechanisms

1.2.4.1 1.4.1 Gears & Reducers

- **Harmonic Drive:** High reduction ratio, zero backlash
- **Planetary Gearbox:** Compact, high torque
- **Application:** Joint actuation with torque amplification

1.2.4.2 1.4.2 Belts & Pulleys

- **Timing Belts:** Synchronous motion
- **Application:** Gripper actuation, linear motion stages

1.3 2. Electrical Systems

1.3.1 2.1 Power Systems

1.3.1.1 2.1.1 Power Distribution Architecture

- **Input:** AC mains (110-240V) or DC supply (24V/48V industrial)
- **Power Tree:**

```
Mains AC → AC-DC Converter → DC Bus (24V/48V)
  → Motor Drivers (servo/stepper)
  → Embedded Controllers (5V/12V regulators)
  → Sensors (3.3V/5V)
  → Vision System (12V)
```

1.3.1.2 2.1.2 Power Budget

Component	Voltage	Current	Power
6x Servo Motors	48V	10A	480W
Controller (Jetson)	12V	5A	60W
Camera System	12V	2A	24W
Gripper Actuator	24V	3A	72W
Total	-	-	**636W**

1.3.1.3 2.1.3 Protection Circuits

- **Overcurrent Protection:** Fuses, circuit breakers
- **EMI/EMC Filtering:** Noise suppression
- **Grounding:** Safety earth, signal ground isolation

1.3.2 2.2 Actuation Systems

1.3.2.1 2.2.1 Servo Motors

- **Type:** Brushless DC (BLDC) or AC servo
- **Control:** Position, velocity, torque modes

- **Feedback:** Encoders (incremental/absolute)
- **Specifications:**
  - Rated torque: 5-20 Nm
  - Speed: 3000 RPM
  - Resolution: 17-20 bit encoders

1.3.2.2 2.2.2 Stepper Motors

- **Type:** Hybrid stepper (1.8° or 0.9° step)
- **Advantages:** Open-loop positioning, no feedback required
- **Disadvantages:** Torque drops at high speed, step loss
- **Application:** Gripper actuation (if cost-sensitive)

1.3.2.3 2.2.3 Linear Actuators

- **Types:**
  - Electric: Ball screw, lead screw
  - Pneumatic: Air cylinders
- **Application:** Z-axis (vertical) motion, gripper open/close

1.3.3 2.3 Motor Drives & Controllers

1.3.3.1 2.3.1 Servo Drives

- **Function:** Commutate motor phases, close position/velocity loops
- **Control Modes:**
  - Position mode (PID)
  - Velocity mode
  - Torque mode
- **Communication:** EtherCAT, CANopen, Modbus, RS-485

1.3.3.2 2.3.2 Drive Tuning

- **PID Parameters:** Proportional, Integral, Derivative gains
- **Auto-tuning:** Some drives support automatic PID calibration
- **Application:** Minimize overshoot, settling time

1.4 3. Electronics & Sensors

1.4.1 3.1 Vision Sensors

1.4.1.1 3.1.1 RGB-D Cameras

- **Models:**
  - Intel RealSense D435/D455
  - Microsoft Azure Kinect
  - Orbbec Astra
- **Outputs:**
  - RGB image (1920x1080 @ 30fps)

  - Depth map (aligned to RGB)
  - Point cloud (XYZ + RGB)
- **Interface:** USB 3.0, USB-C
- **Application:** Object detection, pose estimation

1.4.1.2 3.1.2 Stereo Cameras

- **Principle:** Triangulation from two camera views
- **Calibration:** Stereo calibration for disparity-to-depth
- **Advantages:** Passive, works in all lighting

1.4.1.3 3.1.3 Industrial Cameras

- **Type:** GigE Vision, USB3 Vision
- **Features:** Global shutter, high frame rate (60-120 fps)
- **Application:** High-speed pick-and-place

1.4.2 3.2 Force/Torque Sensors

1.4.2.1 3.2.1 6-Axis F/T Sensor

- **Mounting:** Between robot flange and gripper
- **Measurements:** Fx, Fy, Fz, Tx, Ty, Tz
- **Resolution:** 0.1-1 N force, 0.01-0.1 Nm torque
- **Application:**
  - Grasp force control
  - Collision detection
  - Contact detection (surface touch)

1.4.2.2 3.2.2 Signal Conditioning

- **Amplification:** Low-noise amplifiers
- **Filtering:** Low-pass filter (remove high-freq noise)
- **Calibration:** Zero-offset calibration, load compensation

1.4.3 3.3 Proximity & Limit Sensors

1.4.3.1 3.3.1 Inductive Proximity Sensors

- **Detection:** Metal objects (non-contact)
- **Application:** Detect gripper jaw position, home position

1.4.3.2 3.3.2 Photoelectric Sensors

- **Types:** Through-beam, retro-reflective, diffuse
- **Application:** Object presence detection on conveyor

1.4.3.3 3.3.3 Limit Switches

- **Type:** Mechanical, magnetic (hall-effect)
- **Application:** End-of-travel detection, safety interlocks

1.4.4 3.4 Encoder Systems

1.4.4.1 3.4.1 Rotary Encoders

- **Types:**
  - Incremental (A/B quadrature, index)
  - Absolute (multi-turn)
- **Resolution:** 1000-10000 CPR (counts per revolution)
- **Application:** Joint position feedback

1.4.4.2 3.4.2 Linear Encoders

- **Principle:** Optical/magnetic scale reading
- **Application:** Linear stage position measurement

1.5 4. Control Systems

1.5.1 4.1 Control Theory Fundamentals

1.5.1.1 4.1.1 PID Control

- **Equation:** u(t) = Kp · e(t) + Ki · e(t)dt + Kd · de(t)/dt
- **Tuning Methods:**
  - Ziegler-Nichols
  - Manual tuning
  - Auto-tuning algorithms
- **Application:** Joint position/velocity control

1.5.1.2 4.1.2 Feedforward Control

- **Concept:** Compensate known disturbances (gravity, friction)
- **Equation:** _ff = G(q) + friction_model(q̇)
- **Application:** Improve trajectory tracking

1.5.1.3 4.1.3 State-Space Control

- **Representation:** ẋ = Ax + Bu, y = Cx
- **Controllers:** LQR (Linear Quadratic Regulator)
- **Application:** Advanced multi-variable control

1.5.2 4.2 Motion Control Architectures

1.5.2.1 4.2.1 Cascaded Control Loops

```
Position Loop (outer) → Velocity Loop (middle) → Current Loop (inner)
  10-100 Hz                  1 kHz                    10 kHz
```

1.5.2.2 4.2.2 Trajectory Interpolation

- **Point-to-Point:** Trapezoidal, S-curve velocity profiles
- **Continuous Path:** Spline interpolation

- **Real-Time:** Update setpoints at control frequency

1.5.3 4.3 Force Control

1.5.3.1 4.3.1 Impedance Control

- **Equation:** $F = M \cdot \ddot{x} + D \cdot \dot{x} + K \cdot x$
- **Application:** Compliant contact, assembly tasks

1.5.3.2 4.3.2 Admittance Control

- **Inverse of Impedance:** Compute desired motion from measured force
- **Application:** Human-robot collaboration, delicate grasping

1.5.4 4.4 Real-Time Control Systems

1.5.4.1 4.4.1 Real-Time Operating Systems (RTOS)

- **Examples:** RT-Preempt Linux, FreeRTOS, QNX
- **Requirements:**
  - Deterministic latency (<1 ms jitter)
  - Priority-based scheduling
- **Application:** Hard real-time control loops

1.5.4.2 4.4.2 Control Frequency Requirements

Control Level	Frequency	Latency Req.
Current Control	10-20 kHz	<100 µs
Velocity Control	1-5 kHz	<1 ms
Position Control	100-1000 Hz	<10 ms
Task Planning	1-10 Hz	<100 ms

1.6 5. Embedded Systems & Microcontrollers

1.6.1 5.1 Microcontroller Units (MCU)

1.6.1.1 5.1.1 MCU Selection

- **Low-Level Control:** STM32, Arduino (gripper, simple I/O)
- **Application:** PWM generation, encoder reading, I/O interfacing

1.6.1.2 5.1.2 Communication Interfaces

- **UART/Serial:** Legacy motor controllers
- **SPI/I2C:** Sensor interfaces
- **CAN Bus:** Industrial communication
- **EtherCAT:** High-speed distributed I/O

1.6.2 5.2 Single-Board Computers (SBC)

1.6.2.1 5.2.1 SBC Options

- **NVIDIA Jetson (Nano/Xavier/Orin):**
  - GPU for AI inference
  - Application: Vision processing, deep learning
- **Raspberry Pi:**
  - Low cost, general-purpose
  - Application: Lightweight tasks, prototyping
- **Industrial PC (x86):**
  - High compute, ROS2 master
  - Application: MoveIt planning, system orchestration

1.7 6. Signal Processing & Filtering

1.7.1 6.1 Sensor Data Filtering

1.7.1.1 6.1.1 Low-Pass Filter

- **Purpose:** Remove high-frequency noise
- **Types:**
  - Moving average
  - Exponential smoothing
  - Butterworth filter
- **Application:** Smooth encoder readings, force sensor data

1.7.1.2 6.1.2 Kalman Filter

- **Purpose:** Optimal state estimation with noisy measurements
- **Application:** Fuse multiple sensors (vision + encoder)

1.7.1.3 6.1.3 Median Filter

- **Purpose:** Remove outliers/spikes
- **Application:** Depth image denoising

1.7.2 6.2 Signal Conditioning Circuits

1.7.2.1 6.2.1 Amplification

- **Instrumentation Amplifiers:** High CMRR for differential signals
- **Application:** Strain gauge, load cell amplification

1.7.2.2 6.2.2 Analog-to-Digital Conversion (ADC)

- **Resolution:** 12-16 bit
- **Sampling Rate:** 1-100 kHz
- **Application:** Force sensor, analog encoder readout

1.8 7. Power Electronics

1.8.1 7.1 Motor Drivers

1.8.1.1 7.1.1 H-Bridge

- **Function:** Bidirectional current control for DC motors
- **Components:** MOSFETs, gate drivers
- **Application:** DC motor speed/direction control

1.8.1.2 7.1.2 Three-Phase Inverter

- **Function:** Drive BLDC/AC servo motors
- **Modulation:** PWM (Space Vector Modulation, Sinusoidal PWM)
- **Application:** High-performance servo drives

1.8.2 7.2 DC-DC Converters

1.8.2.1 7.2.1 Buck Converter (Step-Down)

- **Input:** 48V → Output: 12V/5V
- **Efficiency:** 85-95%
- **Application:** Power embedded systems from main DC bus

1.8.2.2 7.2.2 Boost Converter (Step-Up)

- **Application:** Battery-powered systems

1.9 8. System Integration & Interfacing

1.9.1 8.1 Communication Protocols

1.9.1.1 8.1.1 Industrial Ethernet

- **EtherCAT:**
  - Real-time, deterministic
  - Cycle time: <1 ms
  - Application: Servo drive network
- **PROFINET, Ethernet/IP:** Alternatives

1.9.1.2 8.1.2 Fieldbus

- **CAN Bus:**
  - Multi-master, robust
  - Application: Distributed sensors/actuators
- **Modbus RTU/TCP:** Legacy industrial devices

1.9.1.3 8.1.3 USB

- **USB 3.0/3.1:** Camera data transfer
- **USB-Serial:** MCU communication

1.9.2 8.2 Hardware Abstraction Layer (HAL)

1.9.2.1 8.2.1 ROS2_Control Framework

- **Concept:** Standardized interface between controllers and hardware
- **Components:**
  - Hardware Interface (read/write joint states)
  - Controller Manager
  - Controllers (position, velocity, effort)
- **Application:** Portable control code across robot platforms

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1.10 9. Safety & Fault Tolerance

1.10.1 9.1 Safety-Rated Systems

1.10.1.1 9.1.1 Emergency Stop (E-Stop)

- **Category:** SIL 2 / PLd (ISO 13849)
- **Implementation:** Dual-channel, monitored E-stop button
- **Action:** Power cut to motors, safe state

1.10.1.2 9.1.2 Safety PLCs

- **Function:** Monitor safety zones, light curtains, door interlocks
- **Communication:** Safe EtherCAT (FSoE)

1.10.2 9.2 Fault Detection & Diagnosis

1.10.2.1 9.2.1 Sensor Fault Detection

- **Methods:**
  - Range checks (out-of-bounds values)
  - Redundancy (compare dual sensors)
  - Plausibility checks
- **Action:** Switch to fallback mode, alert operator

1.10.2.2 9.2.2 Actuator Fault Detection

- **Following Error Monitoring:** Commanded vs actual position deviation
- **Overcurrent Detection:** Motor overload
- **Action:** Stop motion, trigger alarm

1.11 10. Mechatronics System Integration Map

1.11.1 10.1 Subsystem Dependencies

```
                    CONTROL SYSTEM (Software)
          ROS2 / MoveIt / Vision AI / Task Planner
```

```
 ELECTRICAL POWER               ELECTRONICS
- Power Supply                 - Sensors (Camera,
- Motor Drivers                  F/T, Proximity)
- Distribution                 - Signal Cond.
                     - ADC/DAC
```

```
          ACTUATION (Mechanical)
- Servo Motors → Gearbox → Joints
- Gripper Actuator
- Linkages, Kinematics
```

1.11.2 10.2 Signal Flow

```
Vision Sensor (RGB-D) → USB 3.0 → Jetson (AI Processing)
                                        ↓
                            Object Pose (x,y,z,roll,pitch,yaw)
                                        ↓
                         IK Solver → Joint Angles ( 1.. 6)
                                        ↓
                         Trajectory Planner → Waypoints
                                        ↓
                         Controller Manager → Motor Commands
                                        ↓
               Servo Drives (EtherCAT) → Motors → Joint Motion
                                        ↓
                         Encoders → Position Feedback → Controller
```

1.12 11. Mechatronics Concept to Module Mapping

Mechatronics Concept	Module/Component	Department
Link Dynamics (M, C, G)	Robot URDF, Dynamics Engine	Mechanical
Gripper Mechanism	Parallel Jaw Gripper, Pneumatic/Electric	Mechanical
Power Distribution	48V DC Bus, Regulators	Electrical
Servo Motor Control	Servo Drives (EtherCAT)	Electrical
Motor Drive (H-Bridge/Inverter)	Motor Driver Boards	Electrical
RGB-D Camera	RealSense D435, Vision Pipeline	Electronics
Force/Torque Sensor	ATI F/T Sensor, Data Acquisition	Electronics

Mechatronics Concept	Module/Component	Department
Encoder Feedback	Absolute Encoders, Quadrature Interface	Electronics
PID Control	ros2_control Controllers	Software/Control
Impedance Control	Admittance Controller Node	Software/Control
Real-Time Control Loop	RT-Preempt Kernel, RTOS	Software
EtherCAT Communication	IgH EtherCAT Master, Driver Nodes	Software
Emergency Stop	Safety PLC, E-Stop Circuit	Safety/Elect.
Sensor Filtering	Kalman Filter, Moving Avg Node	Software

1.13 12. Design Considerations & Trade-offs

1.13.1 12.1 Mechanical

- **Stiffness vs Weight:** High stiffness → heavy → slower motion
- **Backlash:** Harmonic drives (zero backlash) vs gearboxes (cheaper, backlash)

1.13.2 12.2 Electrical

- **Voltage Selection:** Higher voltage → lower current → less heating, but safety concerns
- **Motor Sizing:** Continuous vs peak torque requirements

1.13.3 12.3 Electronics

- **Camera Resolution vs Frame Rate:** Higher res → lower FPS
- **Sensor Accuracy vs Cost:** High-res encoders expensive

1.13.4 12.4 Control

- **Sampling Frequency:** Higher → better performance, but more compute load
- **Model-Based vs Learning-Based:** Analytical control (robust) vs RL (adaptive, data-hungry)

1.14 Summary

This vision-based pick-and-place system is a **comprehensive mechatronics integration** spanning:

- **Mechanical:** 6-DOF manipulator, gripper mechanisms, transmission systems
- **Electrical:** Power distribution (48V DC bus), servo drives, motor control
- **Electronics:** RGB-D camera, F/T sensors, encoders, signal conditioning
- **Control:** PID, impedance control, real-time loops (10 kHz current, 1 kHz velocity)
- **Embedded:** Jetson for vision, MCU for low-level I/O, EtherCAT for real-time comms

Each subsystem is tightly coupled, requiring **cross-disciplinary design and validation**.

Next Steps: 1. Create detailed CAD models (mechanical) 2. Design electrical schematics and PCBs 3. Select and procure sensors/actuators 4. Develop control firmware and ROS2 drivers 5. Integrate and test subsystems incrementally

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