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# 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 (α)
  + Link offset (d)
  + Joint angle (θ)
* **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 = μ \* N (friction force)  
  Object weight: W = m \* g  
  Minimum normal force: N = W / (2 \* μ)
* **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, q̇)
* **Gravity Vector:** G(q)
* **Equation:** M(q)q̈ + C(q,q̇)q̇ + G(q) = τ

#### 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:** τ\_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·ẍ + D·ẋ + K·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

## 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 (θ1..θ6)  
 ↓  
 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 |
| 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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